1973-06

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THESIS

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IN A THERMALLY STRATIFIED MEDIUM

by

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June 1973

Approved for public release; distribution unlimited.

Jet Plume Development
in a Thermally Stratified Medium

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1973

ABSTRACT

The behavior of an incompressible jet injected into a stably stratified stagnant reservoir was studied in an attempt to define some new aspects of the thermal pollution problem. This experiment investigated the effects of injection angle, Reynolds Number (influence of turbulence), Rayleigh Number (influence of the total temperature of the jet), and reservoir temperature gradient on jet containment and flow stabilization. The nature of the study prohibited precise analytical evaluation of the results but observed tendencies could be qualitatively scrutinized to evaluate the inherent heat and transport problem. Results indicated the pronounced tendency of a reservoir temperature gradient to inhibit mass transport yet enhance heat transfer characteristics.

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I. INTRODUCTION

With domestic power requirements doubling every ten years, the very formidable problem of increased power generation is compounded by the resulting problem of thermal waste. Regardless of which of the presently considered methods of generation is chosen, its efficiency is governed by the thermodynamics of the heat cycle and therefore the amount of heat rejected. Thus, to satisfy power requirements waste heat must be discharged without disrupting the local environment.

Relying on the oceans and lakes as being the most accessible heat sinks, the problem becomes one of dispersing the hot effluent without upsetting nature's physical and biological balance. The most adverse situation would be to discharge into a thermally stratified stagnant reservoir which lacks such natural dispersion effects as tides and currents. However, this is just the situation which lends itself to laboratory analysis.

An integral part of the problem is the unsteady nature of the axisymmetric discharge. In this light, flow characteristics and tendencies from time of discharge must be followed to maintain the problem's completeness. The influence of discharge angles, Reynolds numbers, and Rayleigh number are the relevant parameters of the problem. Other parameters such as nozzle design and discharge placement have been independently scrutinized by other studies.

Therefore what remains is a basic study of the discharge deflection characteristics of an incompressible jet in a temperature gradient as its angle, temperature, and velocity head are varied.

Basic fluid dynamic studies have been made on laminar and turbulent jets but they have concentrated on jet spreading and in particular on its development in uniform surroundings. These studies have critically analyzed the jet on an almost microscopic scale, deeply scrutinizing the fluid dynamic effects on the jet's velocity profile and consequent spreading. This study is macroscopic by comparison, since the internal characteristics will be utilized only to explain the external or visible pattern of jet development; i.e., its development relative to its surroundings and under the influence of environmental properties (thermally stratified medium). A mixing region will be assumed to exist, but only the fact that transport is taking place, and its relationship to the unique aspects of this problem will be considered. The intent is not to ignore important details but rather to allow the salient features of the problem to dominate the study.

II. EXPERIMENTAL APPARATUS

The experimental apparatus shown in Figure 1 was designed to explore the fluid mechanics of the situation as far as possible within the qualitative nature of this investigation.

APPARATUS

The basic reservoir is a Plexiglas tank with internal dimensions of 15 5/8" W. x 15 3/4" Ht. x 16" D. fabricated from 1/2" plate stock. Along one vertical wall injection ports were installed and along the opposite vertical wall glass thermometers were located to monitor the temperature gradient. A cover made of the same stock as the tank completely enclosed the reservoir and supported a thermocouple probe used to measure the temperature gradient and jet pool temperature. For use as a horizontal and vertical visual reference, 1 x 1 inch grid paper was applied externally to the bottom and back of the tank.

The gravity fed injection fluid for the jet was supplied from a two-quart capacity reservoir mounted on a vertical support platform adjacent to the tank. Vertical movement of this reservoir provided bulk adjustment of the total head from zero to approximately forty inches. Fine adjustment and fluid replenishment was accomplished by valves connecting this tank, by way of a pump, to a one gallon feed water reservoir at the base of the platform. Heating and cooling of the injection fluid was accomplished using

immersible heaters (Figure 2) and ice. This temperature was monitored by a thermocouple mounted just ahead of the tank inlet. Two ounces of vegetable dye were added to the injection water to visually indicate the movement of the jet.

Photographs of the jet deflection and spreading were taken by two Speed Graphic cameras, one mounted above and one situated at the front of the tank. Polaroid High Speed Black and White ASA 3000 4 x 5 sheet film was used with settings of (f-22, 1/200) for both cameras.

FABRICATION

All Plexiglas joints were bonded by saturating with carbon tetrachloride. Even with the temperatures and forces placed on the tank by the reservoir water no failures of the joints occurred. All below-water connections to the tank required some form of sealing. The thermometers, glass type (20 - 230°F. range), were spaced apart vertically one inch, and horizontally one inch, along and from the vertical center line. A Plexiglas plate was installed for additional thickness and holes were drilled for inserting the thermometers with allowance for expansion. The holes were further enlarged and threaded to accommodate a brass plug with a hole in the center for the thermometer. Installation was accomplished by inserting the thermometers from inside the tank and slipping an "O" ring over the shank from the outside. The plug was then used to compress the "O"

ring in the recess at the base of the threaded hole. For protection, a Plexiglas cover enclosed the thermometers where they protruded from the tank. Twenty-one thermometers were mounted in this manner. A less intricate and possibly more satisfactory method for temperature gradient measurement was the use of a temperature probe. Here, a bi-metal thermocouple was placed in an aluminum tube for support and coated with epoxy resin for rigidity. Mounted to the tank cover, it could be positioned within the reservoir along the probe center line and at any depth for 2-D measurement of the temperature profile.

The other critical entry points were the injection ports. Although not as prone to leakage as the thermometers, they did require smooth entrance holes. Therefore, along the vertical center line of the wall opposite the thermometers 0.0330 inch holes were drilled. These were spaced one inch apart from 2 to 14 inches above the inside base of the tank. This hole was enlarged to a depth one half the wall thickness to accommodate a one inch long, 0.0330 I.D. tube inserted from the outside and allowed to protrude for connection of the injection circuit. This insured a smooth flow passage without area discontinuities for axisymmetric jet formation. Using this same procedure, additional probes were installed at each level, one inch either side of the center line, to supply a 45° up and down injection configuration.

A graphic display of the plumbing used for the injection fluid is shown in Figure 2. A bi-metal thermocouple is located just prior to the reducer to record the injection temperature as close as possible to the wall entrance. This and the top mounted thermocouple use Honeywell Brown Electronic read out devices displaying temperature in degrees Fahrenheit. The difference between this temperature and the reservoir temperature at the injection level was recorded and used as a comparison parameter denoted as (ΔT jet).

A small electric driven impeller pump was used to circulate the heated/cooled injection water through the gravity feed tank and maintain the total head at a constant setting by providing make-up water during injection.

Illumination for the cameras was provided by two flood lights positioned on the thermometer side of the tank. Initial tests indicated that if placed too close to the test region or left burning between injections, the lights would heat the reservoir water and disrupt the thermal layers. Therefore, they were used only during the injection sequence.

All external mounting fixtures for the overhead camera and the gravity feed tank were constructed of wood.

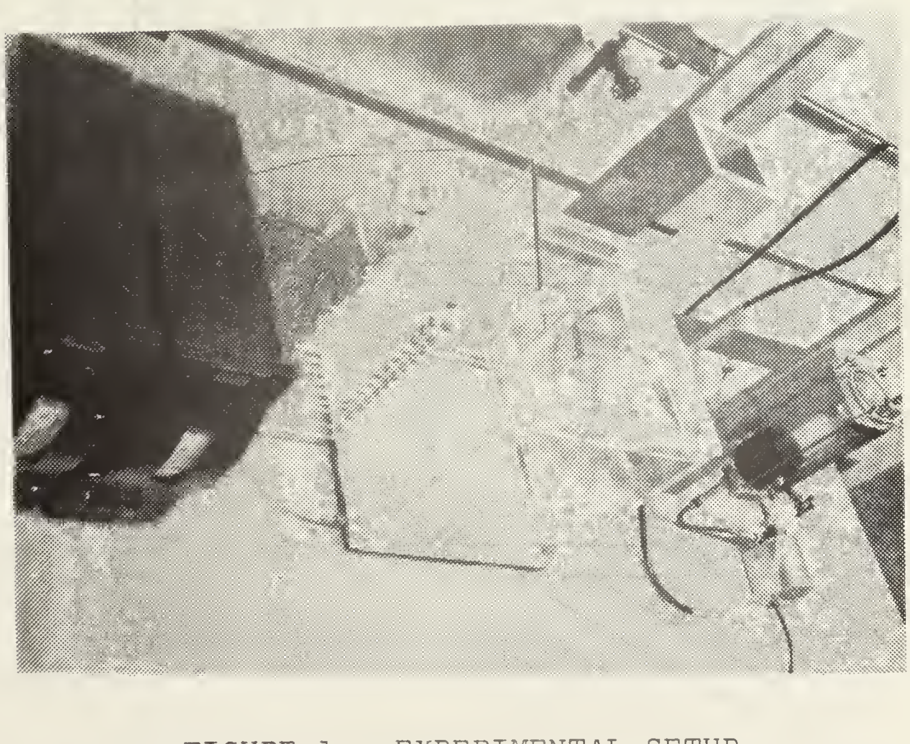


FIGURE 1. EXPERIMENTAL SETUP

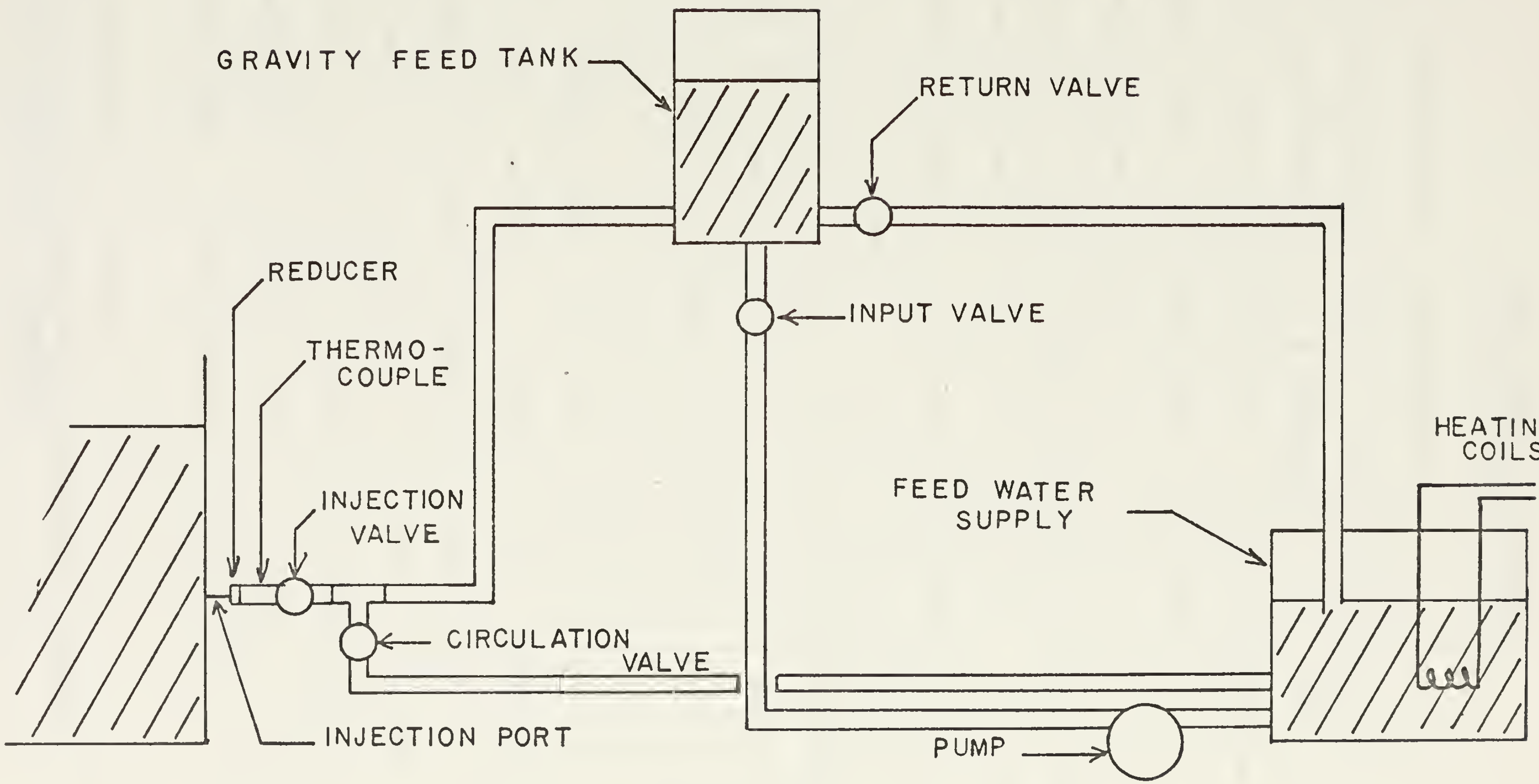


FIGURE 2. JET WATER DELIVERY CIRCUIT

III. EXPERIMENTAL PROCEDURE

The experimental procedure outlined below was followed for each experimental "Run".[1] Initial preparation began by filling the reservoir to a premarked level with 132 degree Fahrenheit water measured with a glass thermometer. A Plexiglas cover was placed over the reservoir and a glass tube was inserted through the hot water layer to the bottom of the tank to feed 60 degree Fahrenheit water (measured by the same thermometer) below the hot water. Flow rate was adjusted by means of a valve on the gravity feed tank which supplied the cold water. This was continued until the level in the reservoir reached a second pre-marked height. This resulted in a half-and-half mixture of hot and cold water which was left undisturbed for two hours, allowing a temperature gradient to form and stabilize by molecular diffusion.

The thermocouple probe was affixed to the cover and lowered into the bath. An earlier test with the cold water mix, dyed for identification, indicated that the thermal layers were not disturbed by the probe's movement. Therefore, with discretion, the probe was manipulated to record the temperature variation within the bath. Initial readings indicated that a strong temperature gradient existed from

[1] Term used to indicate experiments performed in one specific temperature gradient

three inches above to two inches below the five-inch level of the tank. Therefore five inches from the bottom of the tank was chosen as a reference level where the three injection angles would be carried out. The temperature in the tank was recorded at these levels to establish the thermal gradient for each "Run". This thermocouple and its readout device in addition to the injection water thermocouple were calibrated against the thermometer used in preparing the reservoir. (See Appendix A.)

Since the preparation of the bath was time consuming, various injection configurations were performed with one bath as long as the temperature gradient remained stable or the injection dye didn't obscure results. The temperature remained stable for approximately one hour within the temperature gradient region of interest.

To attain the desired temperature of the jet at the tank entrance the injection water was circulated continuously through the feed water supply tank where either heating coils or ice was placed. A bypass placed prior to the injection valve and the reducer insured complete circulation of the injection water circuit and was kept in place until a stable temperature was reached at the injection temperature pickup. With the adjustable feed tank fixed at the desired height the bypass was closed and the fluid level adjusted to the desired head using the input valve at the bottom of the tank. This height, as well as all other length measurements, was made with a scale marked to a sixteenth of an

inch. With the injection head and temperature stabilized, the reducer was connected to the injection port. The resulting plume formation was recorded on film, while the inlet temperature was monitored for any possible variation in its setting.

To keep frictional losses to a minimum and ensure reliability of injection head measurement, a large diameter delivery circuit to injection diameter was utilized. To evaluate its effectiveness, a momentum study was conducted and the results are contained in Appendix B. Since throughout this experiment, analysis is by comparison, any losses in the system should not affect conclusions. Using visual means to identify turbulence further removes the necessity for precise flow measurements.

Overall accuracy of experimental parameters is within one degree for all temperature measurements and one-sixteenth of an inch for all displacement and total head measurements; this lies within the experimental tolerances of this investigation.

The most critical factor which could shadow valid results was whether the dye would change the density or miscibility of the injection fluid. All indications are that the vegetable dye solution is miscible in water. The specific gravity was checked for density differences and found to be 1.0015 at 59 degrees Fahrenheit for the dye solution versus 1.0005 for the reservoir water at the same temperature.

IV. RESULTS AND DISCUSSION

This experimental study provided excellent visual definition of jet plume formation, transition to turbulence and laminar mixing, as well as jet penetration in thermal layers. The behavior of an incompressible fluid is drastically altered when injected into a thermally stratified reservoir as compared with injection into a uniform bath. The configuration can alter the jet's apparent Reynolds number (onset of turbulence), mixing path, and settling level. Results arranged as graphical plots and actual photographs of jet plume formation are contained in Appendix C and D.

To cope with the complex nature of plume formation a simplification is proposed for easier point by point analysis. Realizing the obvious interdependence of the dependent variable forming the momentum relation for the injection jet and the unsteadiness or time dependence of the problem, it is suggested that certain functional variables be individually and independently partitioned.

The momentum relation will be treated as a superposition of effects from among the following "independent functions":

a. Reynolds number

b. Jet injection angle

c. Temperature of the injectant

d. Injection velocity

e. Temperature gradient of reservoir

f. Molecular diffusion

g. Buoyancy force

h. Heat transfer

i. Density of injectant

j. Jet surface shear forces or boundary layer shear

Items a through e were directly studied in this report. The remainder were not specifically analyzed.

A. THERMALLY STRATIFIED RESERVOIR

1. Reynolds number

A jet subjected to Reynolds number changes ranging from laminar to turbulent precipitates drastic behavioral changes in plume formation. This behavior, generally predictable in uniform surroundings, is altered appreciably by a temperature gradient. Mass transport between the jet and its surroundings is restricted even when the jet has become fully turbulent. Instead of a constantly expanding plume, the jet remains contained (lateral to horizontal) yet turbulent. Jet dispersion of even a laminar jet is more pronounced in a uniform bath than in a thermally stratified one. This can be seen in injection No. 105 where a cold laminar jet in a gradient shows only a slight tendency towards becoming turbulent, whereas in injection No. 110 the same jet in a uniform bath exhibits earlier development and transition to turbulent flow.

2. Jet injection angle

Three jet angles were used to investigate the effects of the temperature gradient on the jet's trajectory.

Pronounced effects were observed when the jet angle was directed into an adverse temperature gradient relative to the jet's injection temperature. For example, a hot laminar jet injected down into a cold region would be carried up into the hotter regions and, having apparently lost its temperature reinforcing buoyancy forces, would return to the injection level. Its path would assume that of oscillatory motion, almost completing one period, as depicted by injection No. 21. An interesting effect was that a horizontally injected hot jet would rise farther in a uniform bath than in a stratified one. This can be seen in injection No. 114 and No. 100. The fact that a reinforcing gradient, or for that matter any gradient, retards dispersion reveals the inherent pollution problem in a naturally stratified reservoir even if injection angle is used for pollution control. An interesting approach would be to use an oscillating discharge angle for better dispersion. At least the jet should be angled into the adverse temperature gradient for better discharge heat dissipation.

3. Jet temperature

For all laminar injections into a thermally stratified reservoir from arbitrary injection angles the jet temperature affects the vertical momentum of the jet, as would be expected. With increasing jet temperatures the jet propagates higher into the hotter layers. With a uniform bath, propagation proceeds to the surface; but in a temperature stratified bath a steady-state limit of

propagation is reached at a level below the surface. Therefore temperature stratification continues to reinforce the buoyancy effects of a hot jet, but likewise limits the displacement as temperature equilibrium is reached.

4. Jet Velocity

The total head or Reynolds no. effect on jet development in general reinforces thermal gradient effects. A hot jet injected into a favorable gradient is carried farther into the gradient with corresponding increased influence on plume development. Reduced heat loss from increased momentum results in increased settling heights of the jet. Similar results occurred for cold jets, as well as when the jet angle was horizontal.

5. Thermally stratified gradient

Temperature gradient effect is the principle concern of this study and, as can be seen from the previous results, its effect is not independent but is strongly dependent on other variables. Some general characteristics can be observed, the most common of which is that the thermal gradient suppresses radial dispersion. Jet mixing is therefore delayed, resulting in a very well defined jet trajectory profile. Therefore, it seems that the temperature gradient's primary effect is to reduce the region of transport around the jet and compress the boundary layer between jet and reservoir. This characteristic feature produces consistent curtailment of horizontal momentum by transferring it to vertical momentum through increased buoyancy forces.

V. CONCLUSION

The results of this experimental investigation of jet flow behavior under the influence of a temperature gradient in a stagnant reservoir indicate the following trends:

1. A temperature gradient suppresses the diffusion of a jet along its boundary and therefore delays the formation of characteristic turbulent flow.
2. Varying the injection temperature has the effect of amplifying buoyancy effects and altering the balance of horizontal and vertical momentum.
3. Depending on the jet-to-reservoir temperature, a thermal gradient can suppress buoyancy effects.
4. In a laminar jet, buoyancy forces can be reversed by injecting into an adverse thermal gradient. The jet's trajectory is altered in such a manner as to become oscillatory through the temperature profile.
5. From displacement results of hot and cold jet trajectories, momentum dissipation is greater for a hot jet injected into a cold region than for a cold jet injected into a hot region. Therefore heat transfer between jet and reservoir is more effective from a hot jet to a cold region than from a cold jet to a hot region.

APPENDIX A

TEMPERATURE CALIBRATION

The three temperature measuring devices were calibrated against each other (Table 1, this Appendix) and corrections were made to recorded temperature data so that all temperatures in this report are relative to the thermometer.

TABLE 1

TEMPERATURE CALIBRATION DATA

Thermocouple (1) °F	Thermocouple (2) °F	Thermometer °F
131	118	127
125	116	123
117	108	116
110	100	108
103	92	101
95	85	92
88	78	87
84	74	82
79	70	78
73	63	72
54	44	54

Thermocouple (1) - registers injection temperature
Thermocouple (2) - registers reservoir temperature
Thermometer - registers mixing temperatures

APPENDIX B

INJECTION LOSSES

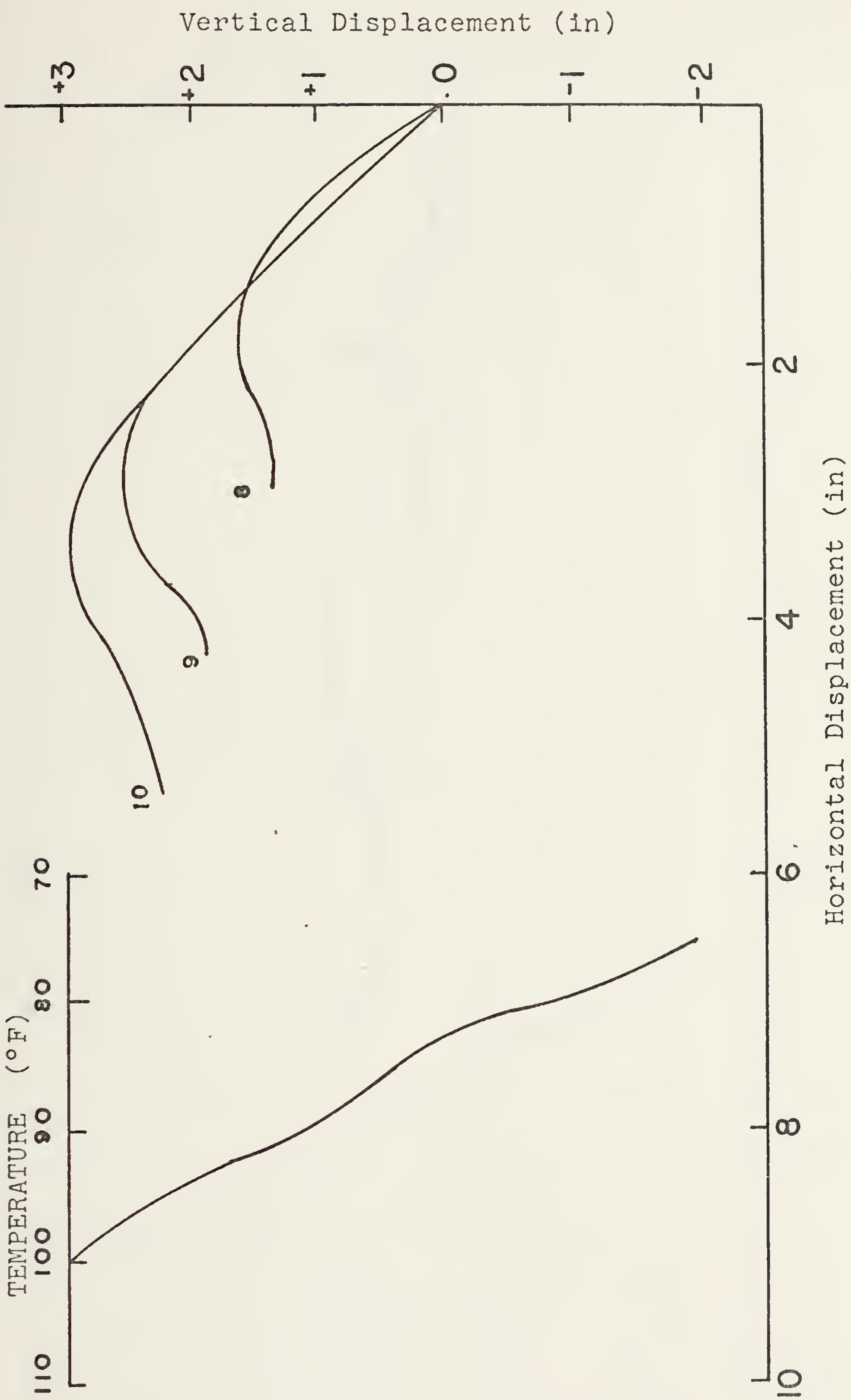
A conservation of energy analysis was performed in an attempt to establish a relative scale for the losses in the injection system for credibility of the head measurements. Horizontal and vertical jet displacement data was recorded for various constant head settings. It was assumed that all losses were at the wall exit and a vena contracta analysis was applied. Therefore using Bernoulli's equation for the theoretical exit velocity and then using trajectory methods for determining the actual exit velocity, a velocity coefficient was calculated for the exit at the wall. (See Table 1, this Appendix.)

TABLE 1

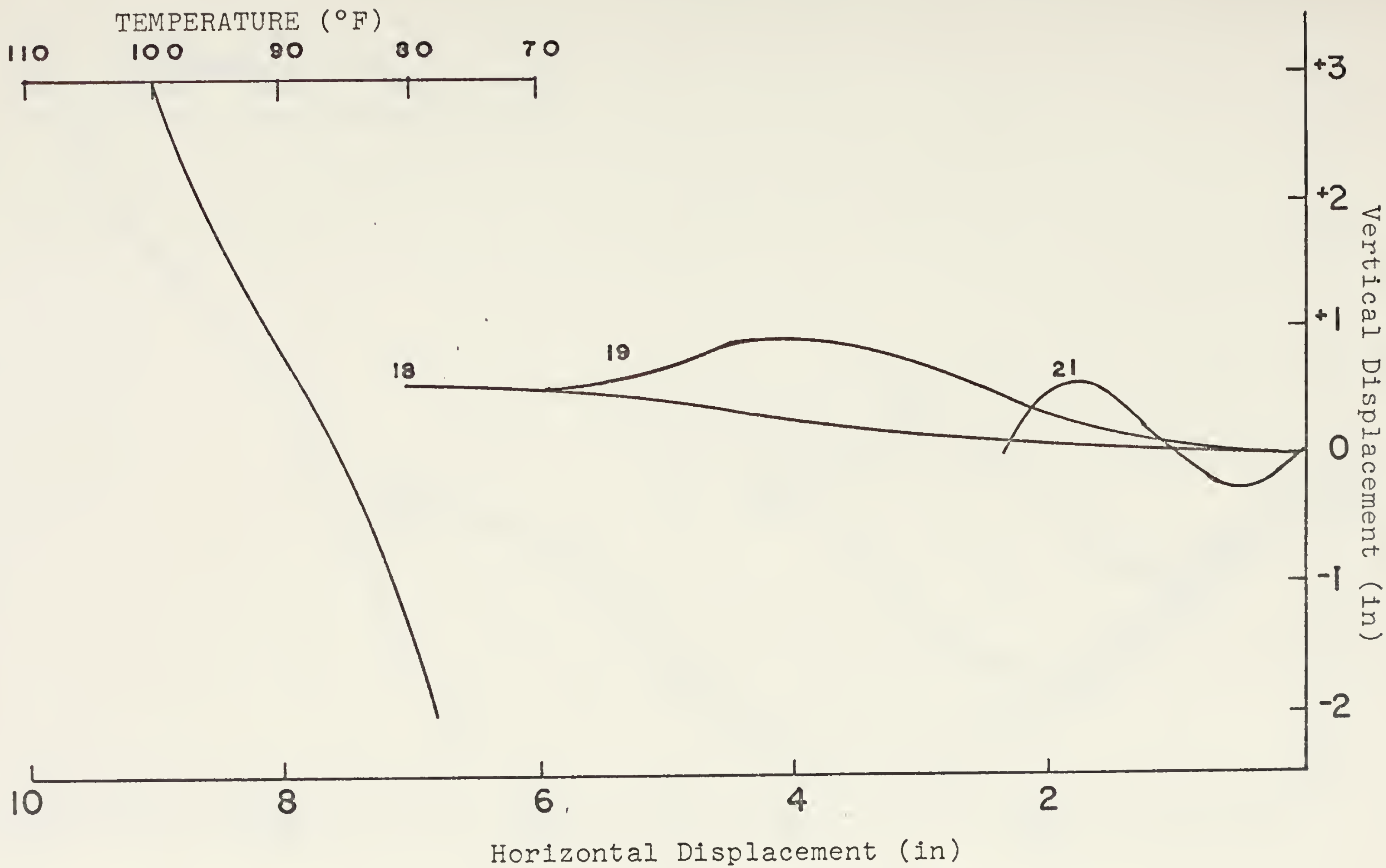
HEAD LOSS DATA

Head (in)	Vert. Disp. (in)	Horo. Disp. (in)	Theo. Vel. (Ft/sec)	Act. Vel. (Ft/sec)	$C_V=\frac{V_a}{V_t}$
35	2	7	13.7	5.7	.42
26	2	6	11.8	5.0	.42
20	2	4	10.4	3.3	.32
10.5	2	2	7.5	1.6	.22

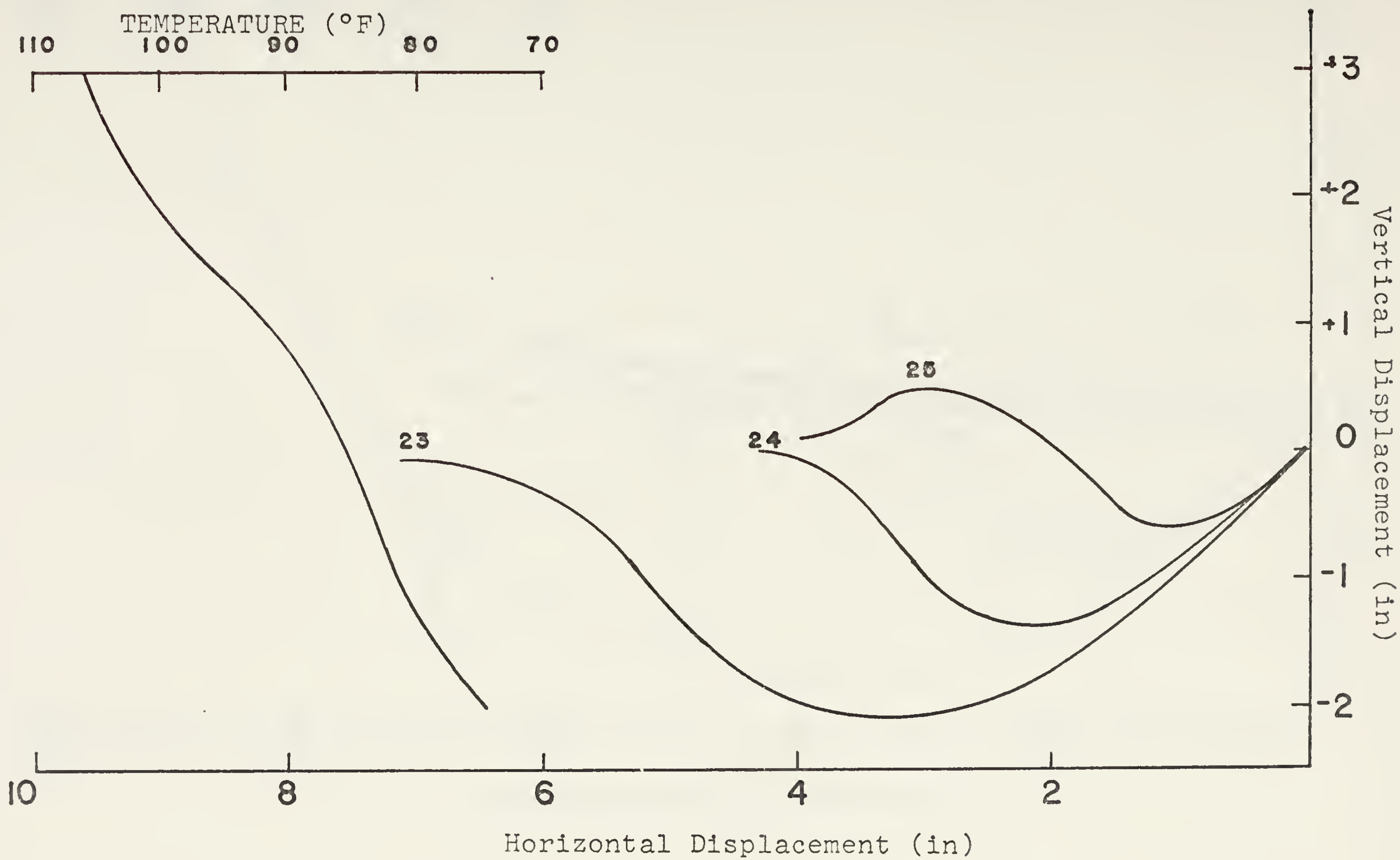
APPENDIX C



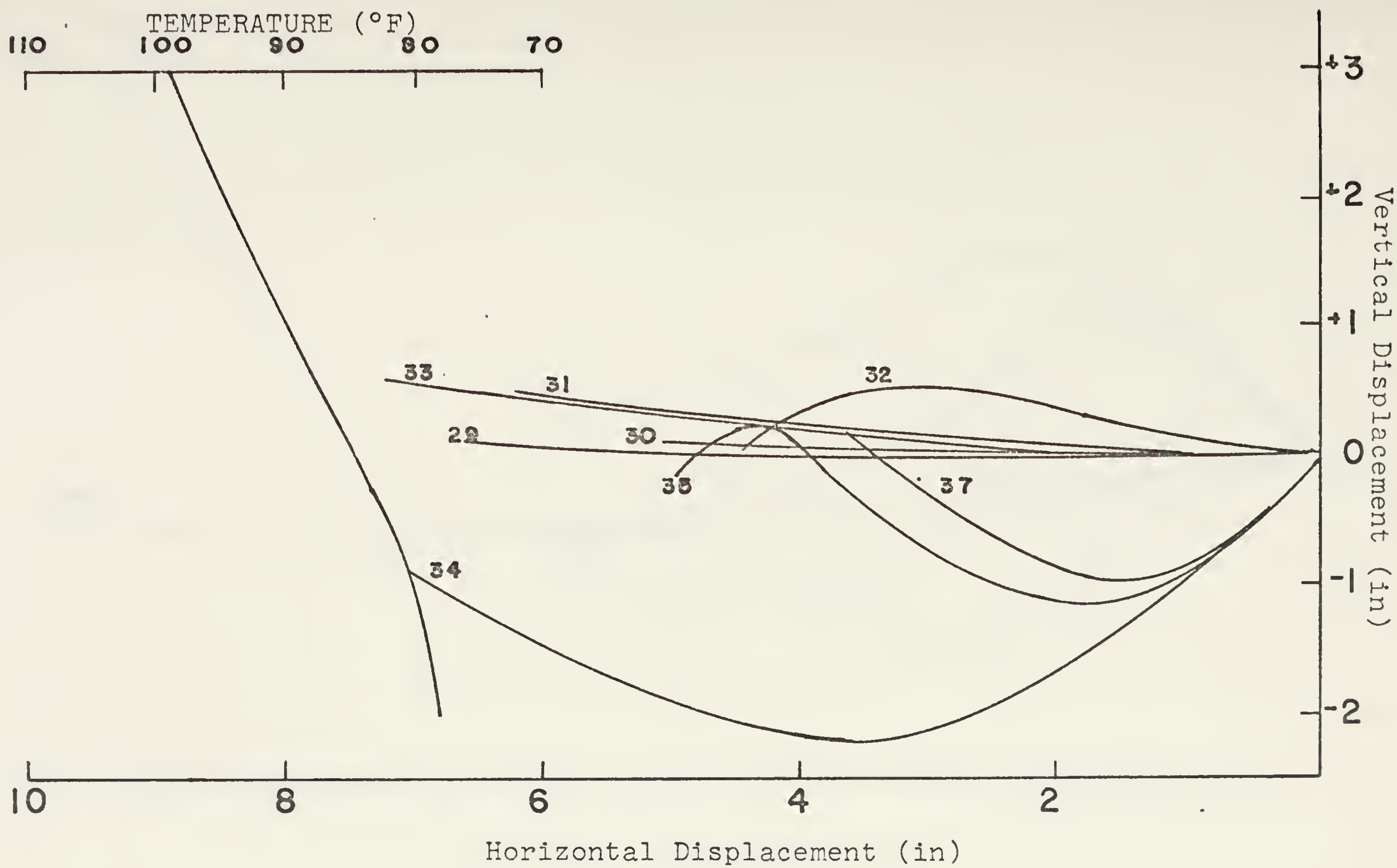
FLOW PROFILE AND TEMPERATURE GRADIENT RUN #2



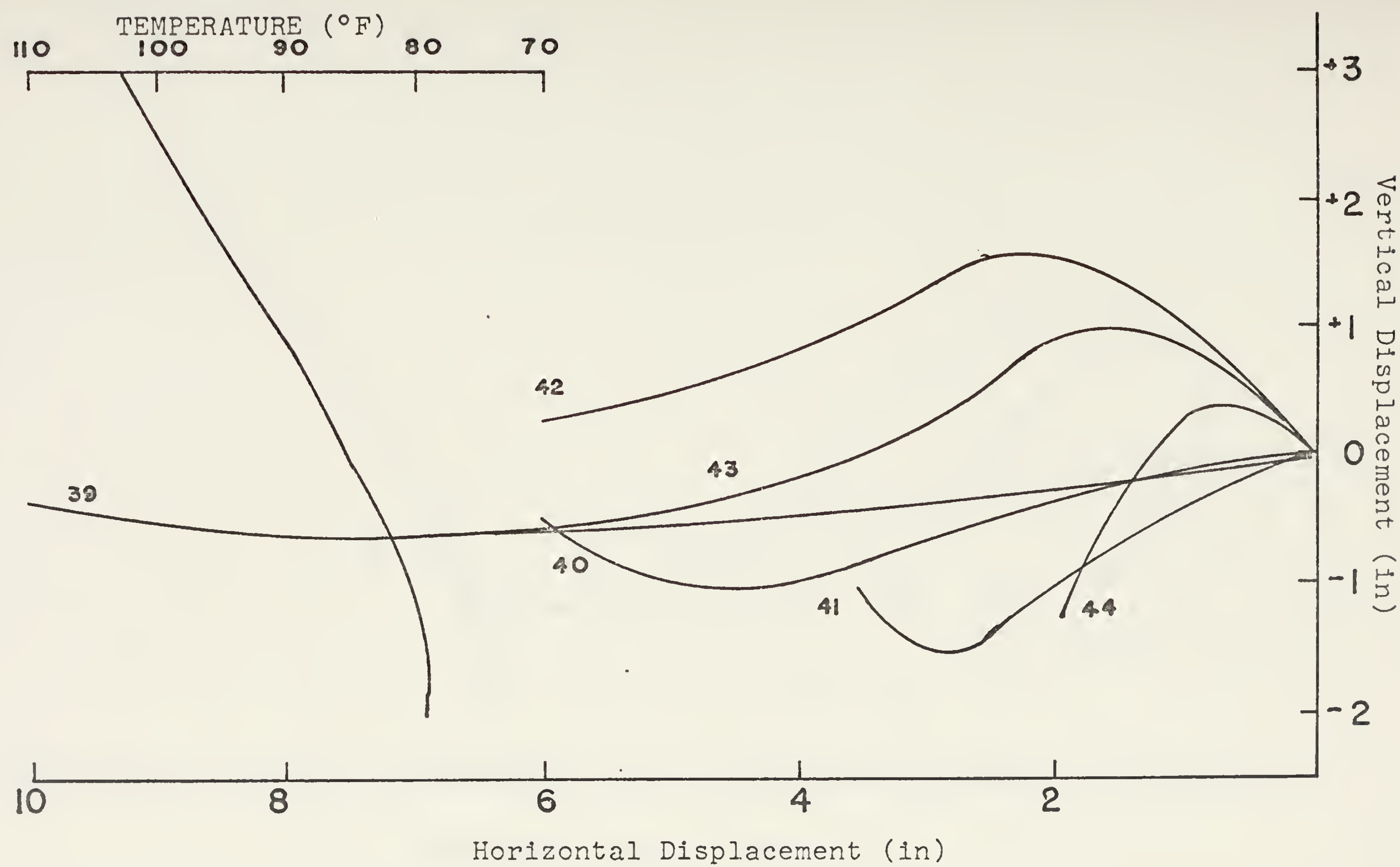
FLOW PROFILE AND TEMPERATURE GRADIENT RUN # 4



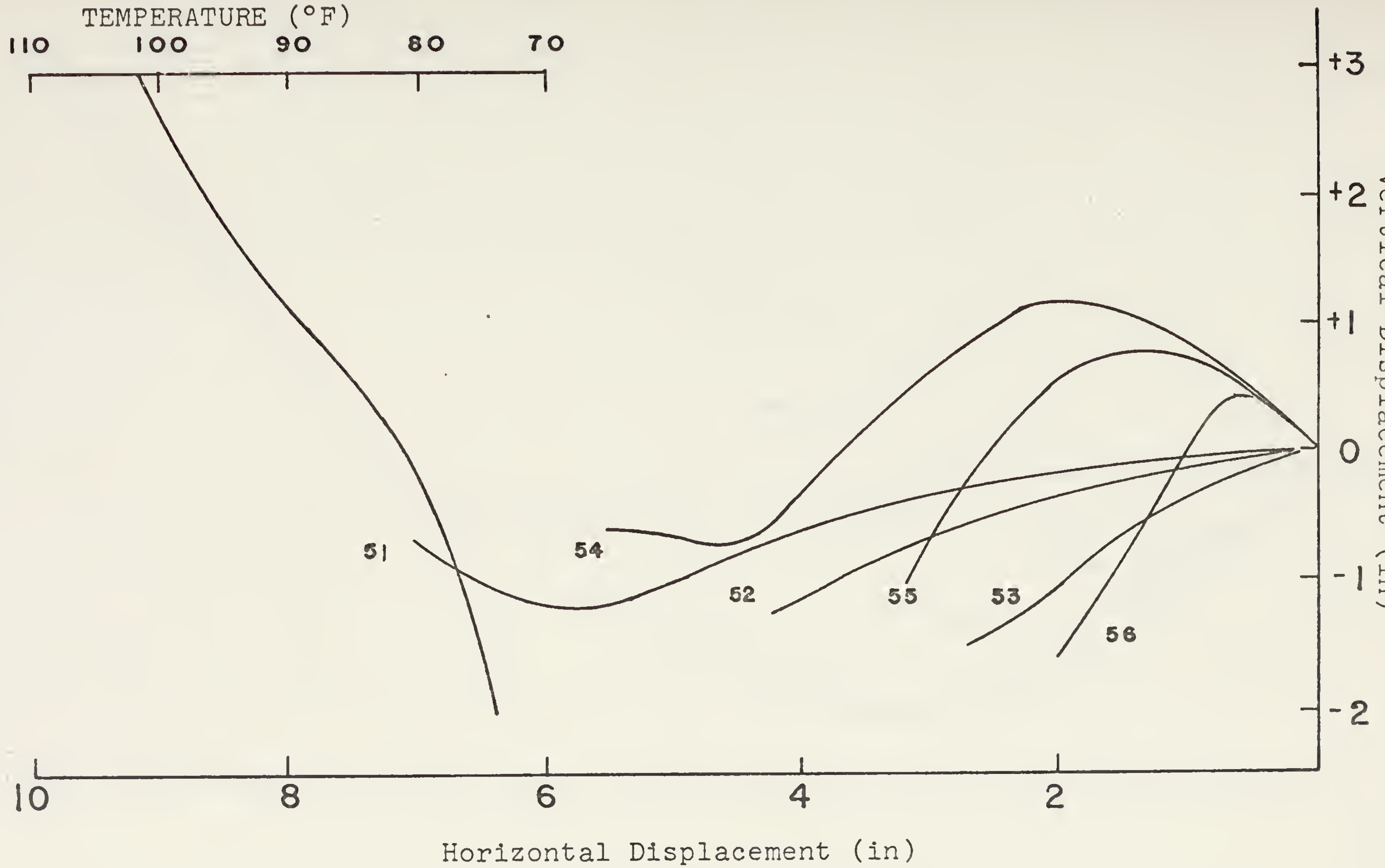
FLOW PROFILE AND TEMPERATURE GRADIENT RUN #5



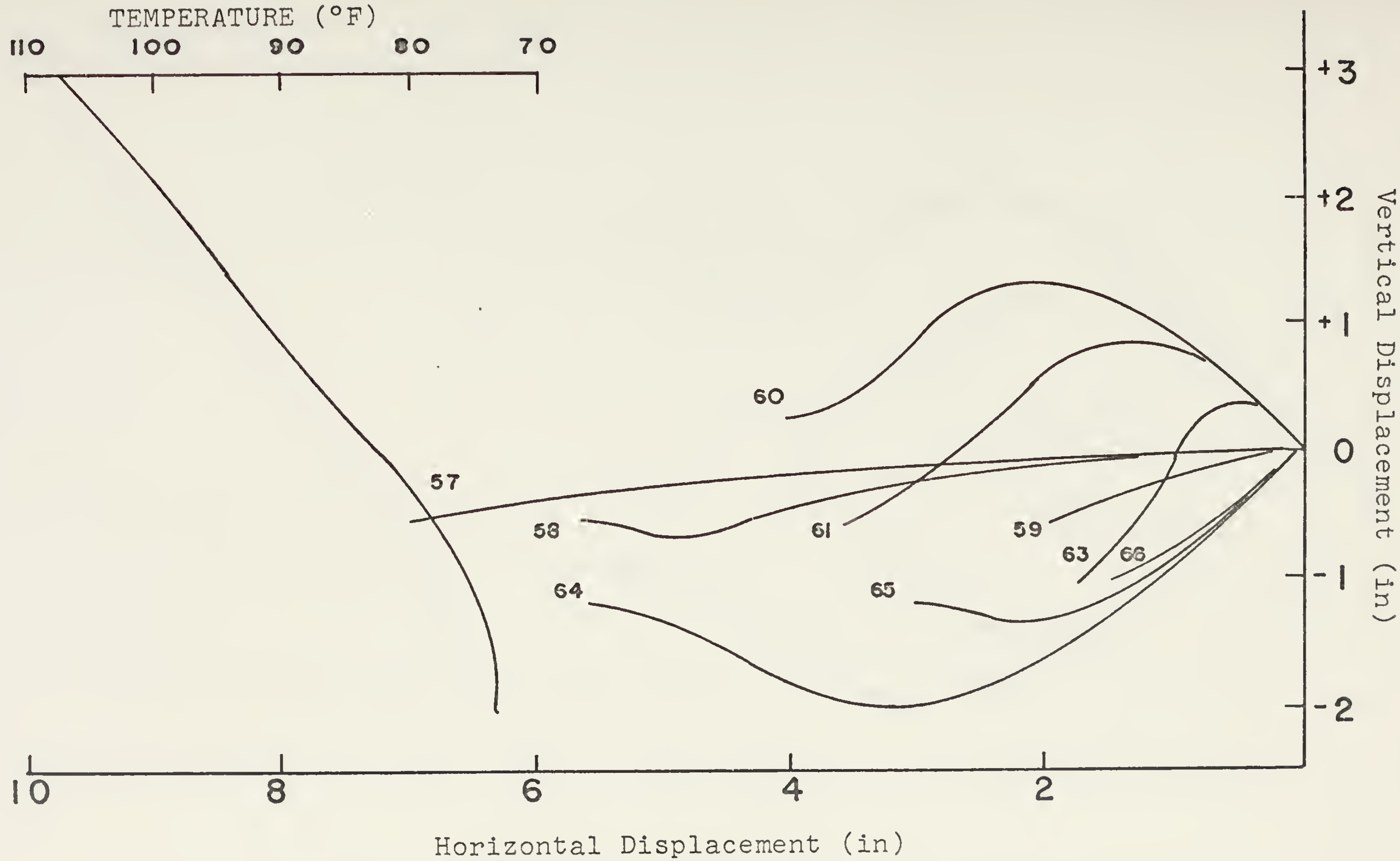
FLOW PROFILE AND TEMPERATURE GRADIENT RUN #6



FLOW PROFILE AND TEMPERATURE GRADIENT RUN #7

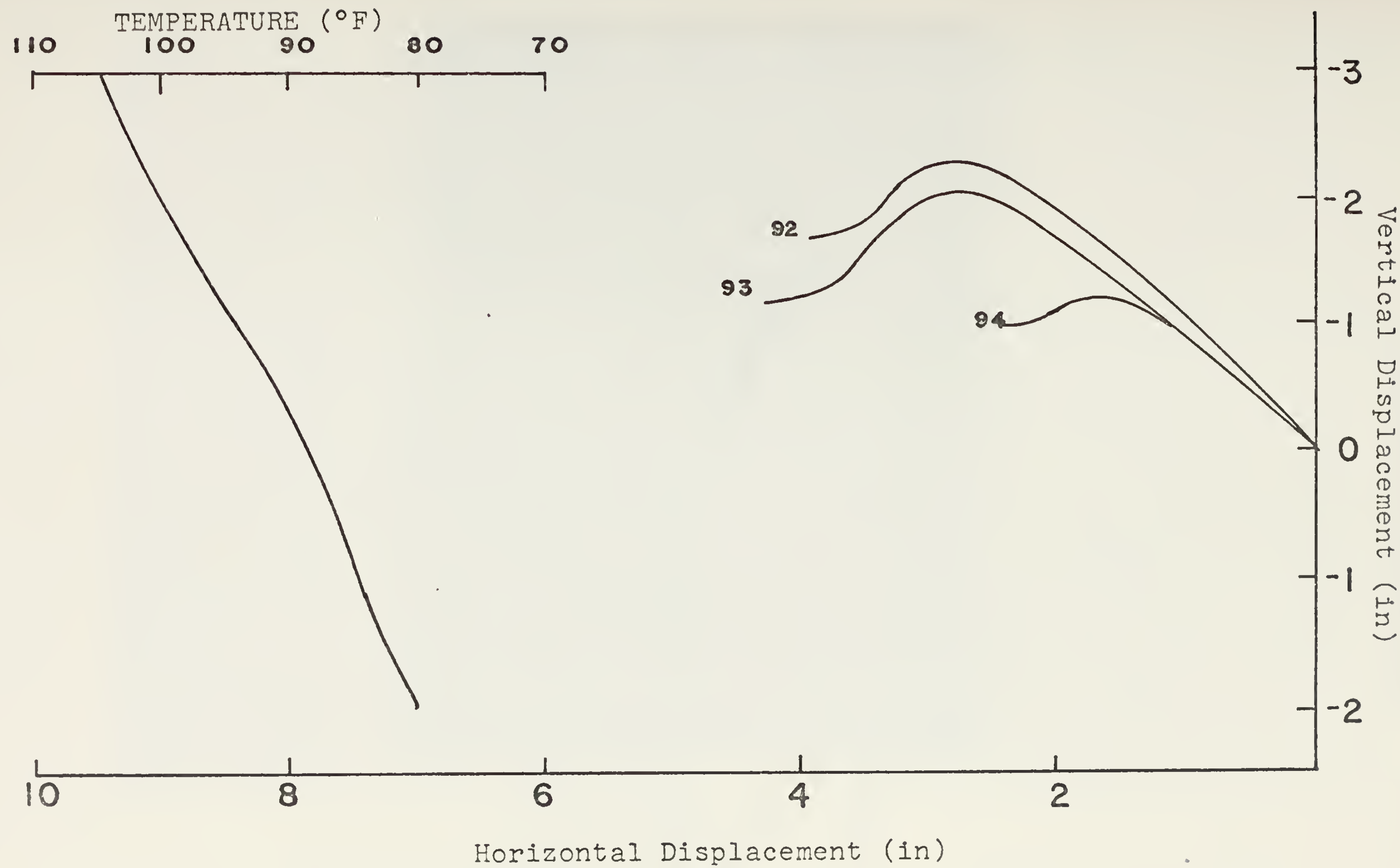


FLOW PROFILE AND TEMPERATURE GRADIENT RUN #8



FLOW PROFILE AND TEMPERATURE GRADIENT RUN #9

FLOW PROFILE AND TEMPERATURE GRADIENT RUN #10



FLOW PROFILE AND TEMPERATURE GRADIENT RUN # 13

APPENDIX D

FREE JET PROFILE DATA

Injection:

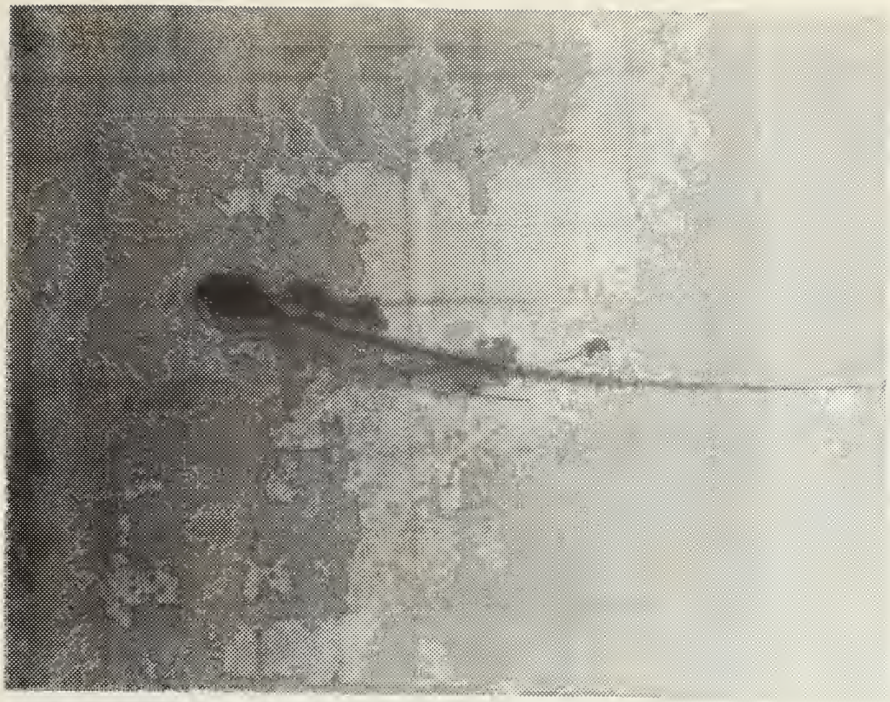
No. 1

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
0.5" H_2O

ΔT JET:
33° F



Injection:

No. 2

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.0" H_2O

ΔT JET:
33° F

Injection:

No. 2

VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
1.0" H_2O

ΔT JET:
33° F

Injection:

No. 3

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
33° F

Injection:

No. 4

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
.5" H_2O

ΔT JET:
33° F

Injection:

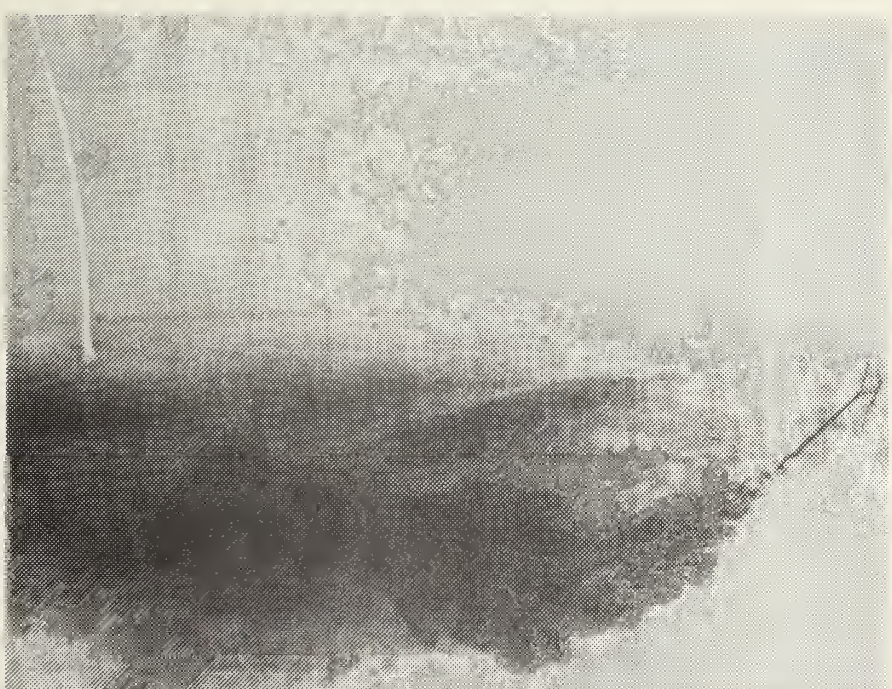
No. 5

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.0" H_2O

ΔT JET:
33° F



Injection:

No. 6

VIEW:
SIDE

ANGLE"
DOWN

TOTAL HEAD:
1.5" H_2O

ΔT JET:
33 °F

Injection:

No. 7

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
33°F

Injection:

No. 7

VIEW:
TOP

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
33°F

Injection:

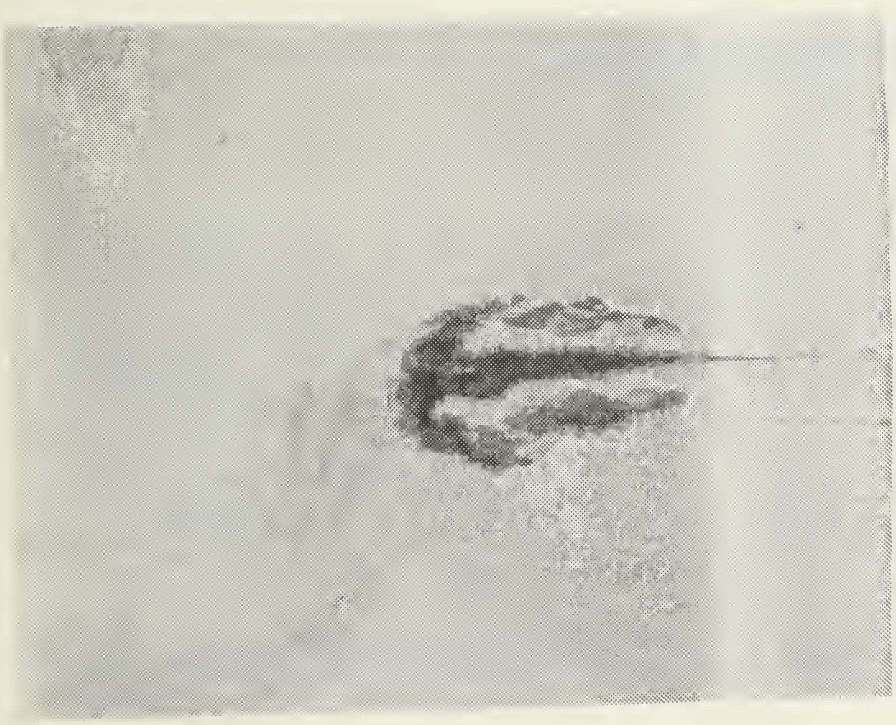
No. 8

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
33°F



Injection:

No. 8

VIEW:
TOP

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
33°F

Injection:

No. 9

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.0" H_2O

ΔT JET:
33°F

Injection:

No. 9

VIEW:
TOP

ANGLE:
UP

TOTAL HEAD:
1.0" H_2O

ΔT JET:
33°F

Injection:

No. 10

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.5" H_2O

ΔT JET:
32°F

Injection:

No. 12

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.5" H_2O

ΔT JET:
18°F

Injection:

No. 13

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.0" H_2O

ΔT JET:
14°F

Injection:

No. 14

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.0" H_2O

ΔT JET:
17°F

Injection:

No. 15

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
17°F

Injection:

No. 15

VIEW:
TOP

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
17°F

Injection:

No. 16

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
10°F

Injection:

No. 17

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:

1.5" H_2O

ΔT JET:
22°F

Injection:

No. 18

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.0" H_2O

ΔT JET:
18°F

Injection:

No. 18

VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
1.0" H_2O

ΔT JET:
18°F

Injection:

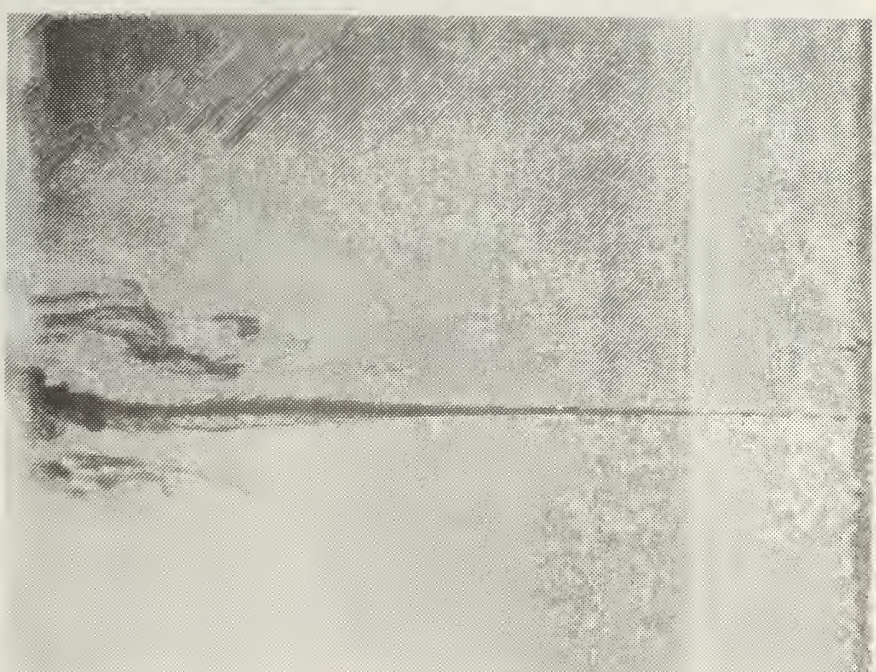
No. 19

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
0.5" H_2O

ΔT JET:
20°F



Injection:

No. 19

VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
0.5" H_2O

ΔT JET:
20°F

Injection:

No. 20

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
18°F

Injection:

No. 21

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
0.5" H_2O

ΔT JET:
20°F

Injection:

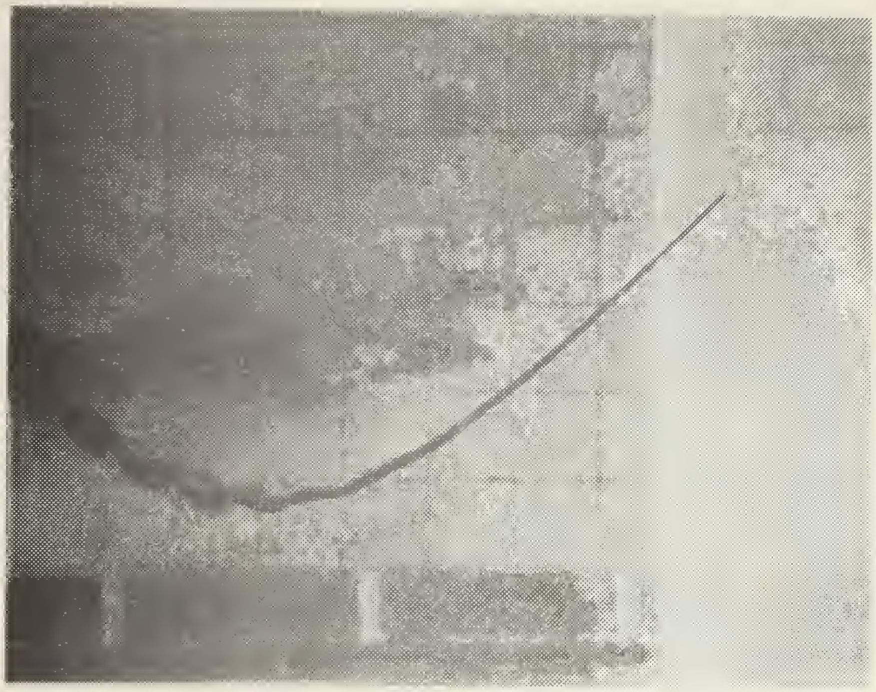
No. 21

VIEW:
TOP

ANGLE:
DOWN

TOTAL HEAD:
0.5" H_2O

ΔT JET:
20°F



Injection:

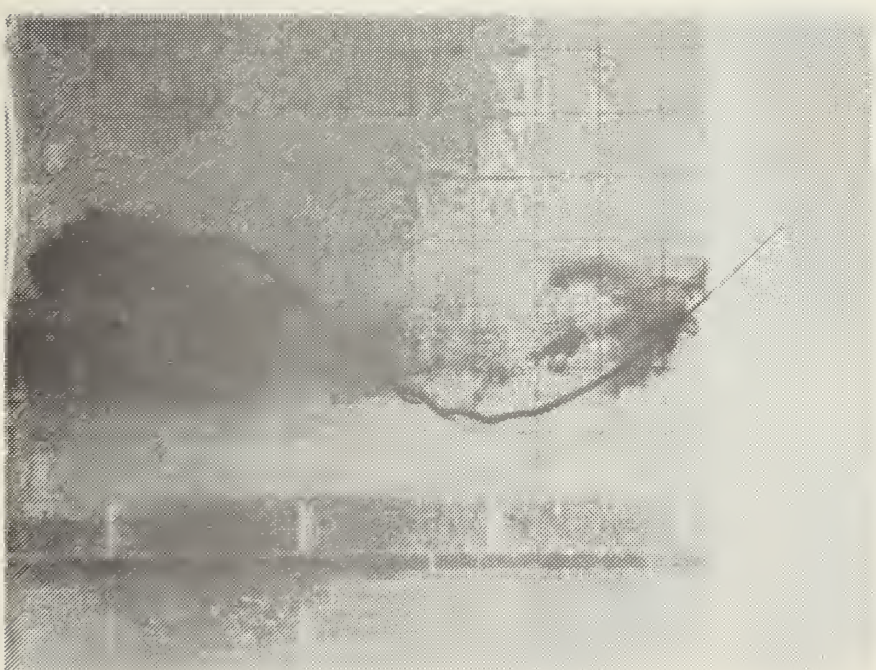
No. 22

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.5" H_2O

ΔT JET:
16°F



Injection:

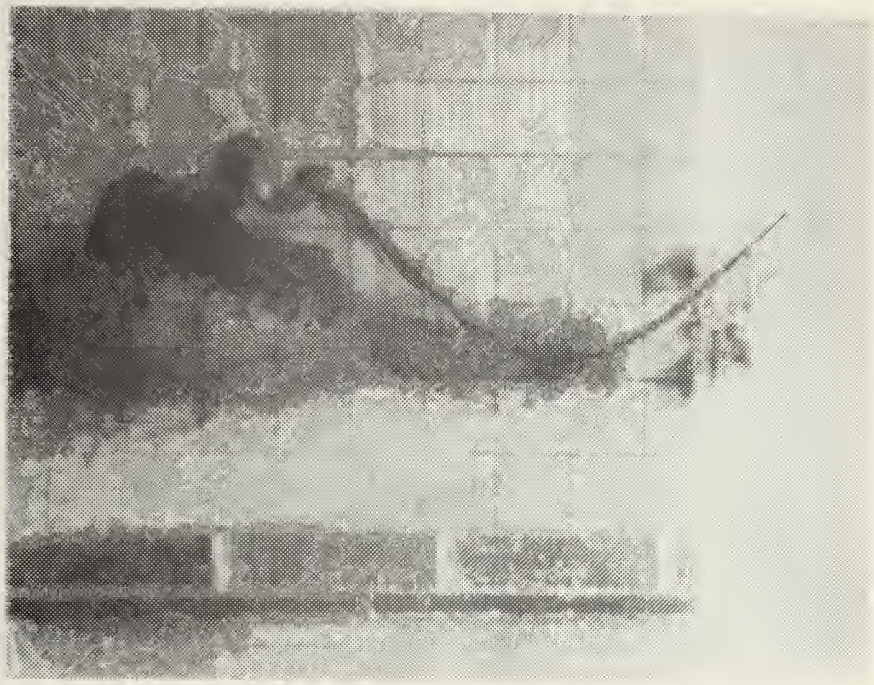
No. 23

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.5" H_2O

ΔT JET:
20°F



Injection:

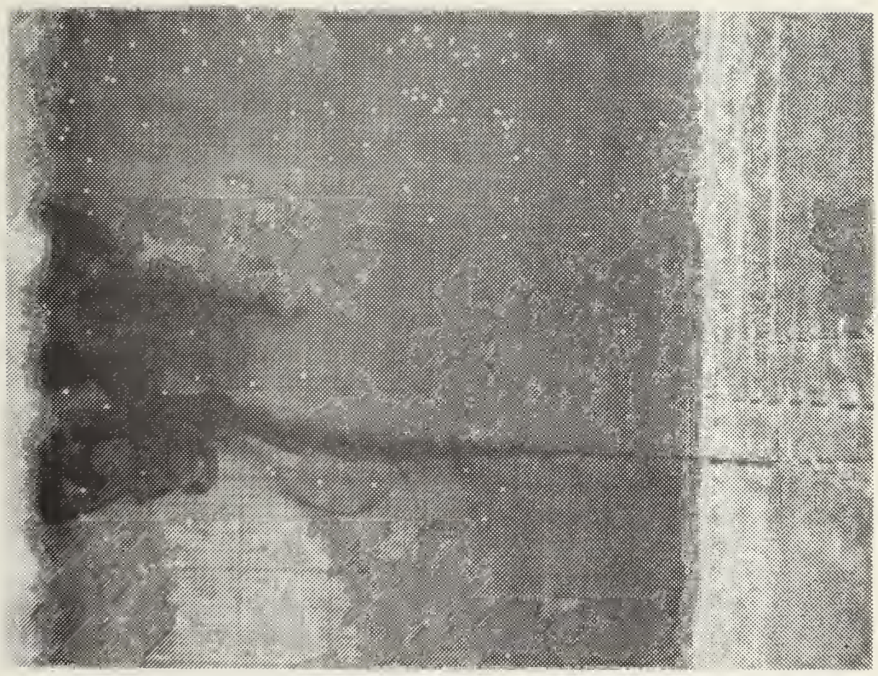
No. 24

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.0" H_2O

ΔT JET:
18°F



Injection:

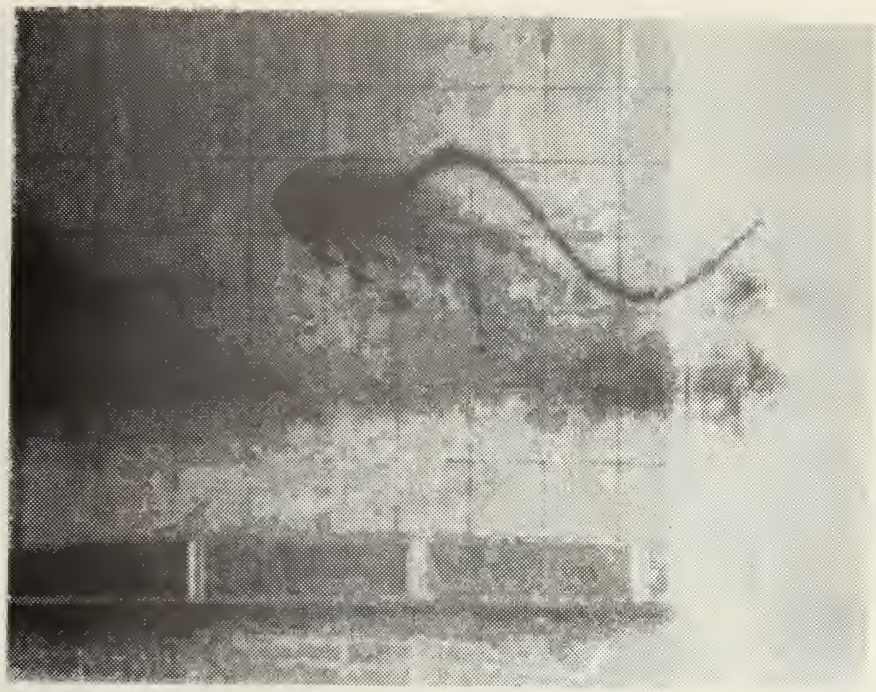
No. 24

VIEW:
TOP

ANGLE:
DOWN

TOTAL HEAD:
1.0" H_2O

ΔT JET:
18°F



Injection:

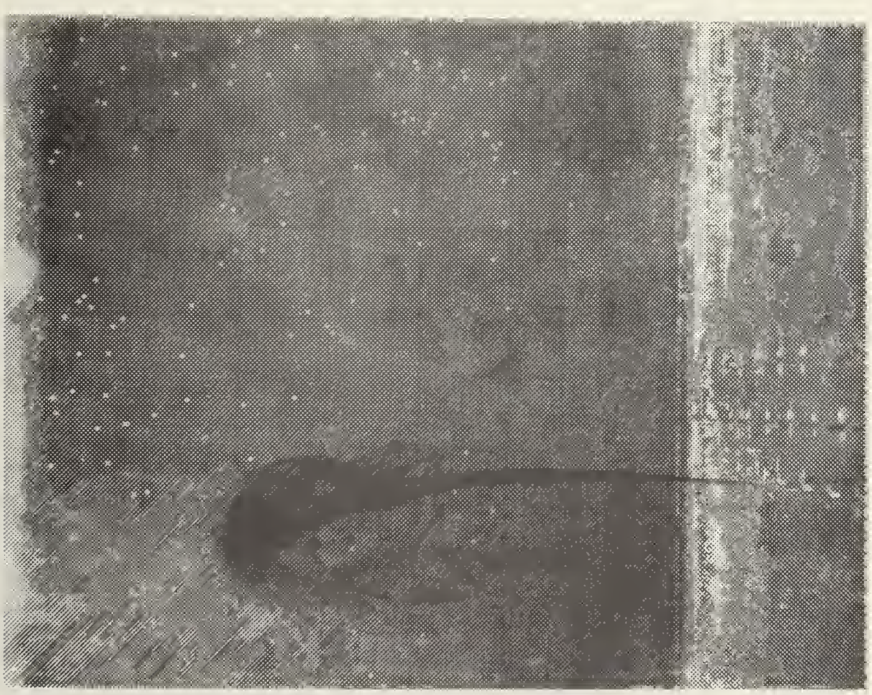
No. 25

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
0.5" H_2O

ΔT JET:
17°F



Injection:

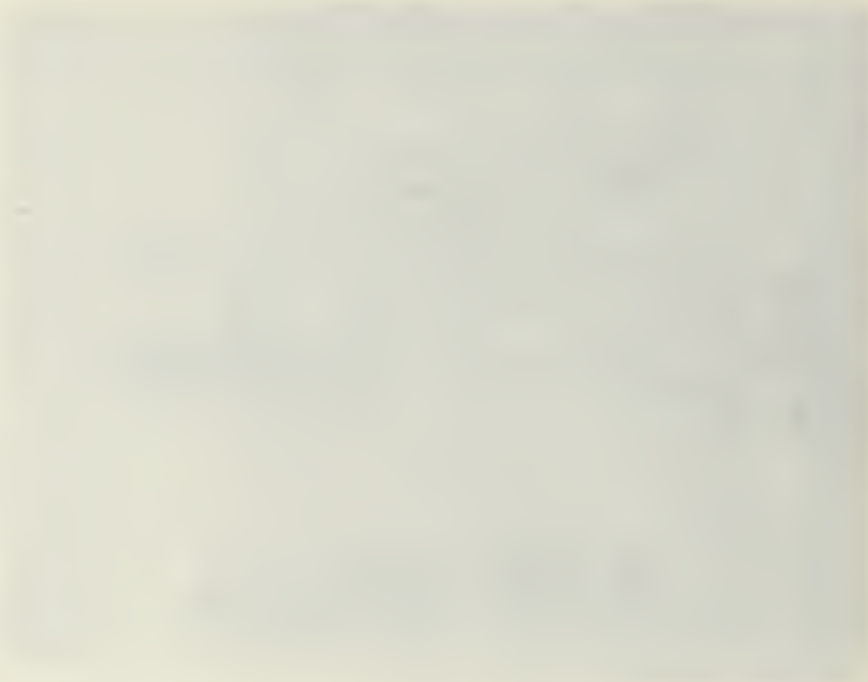
No. 25

VIEW:
TOP

ANGLE:
DOWN

TOTAL HEAD:
0.5" H_2O

ΔT JET:
17°F



Injection:

No. 26

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1" H_2O

ΔT JET:
10°F

Injection:

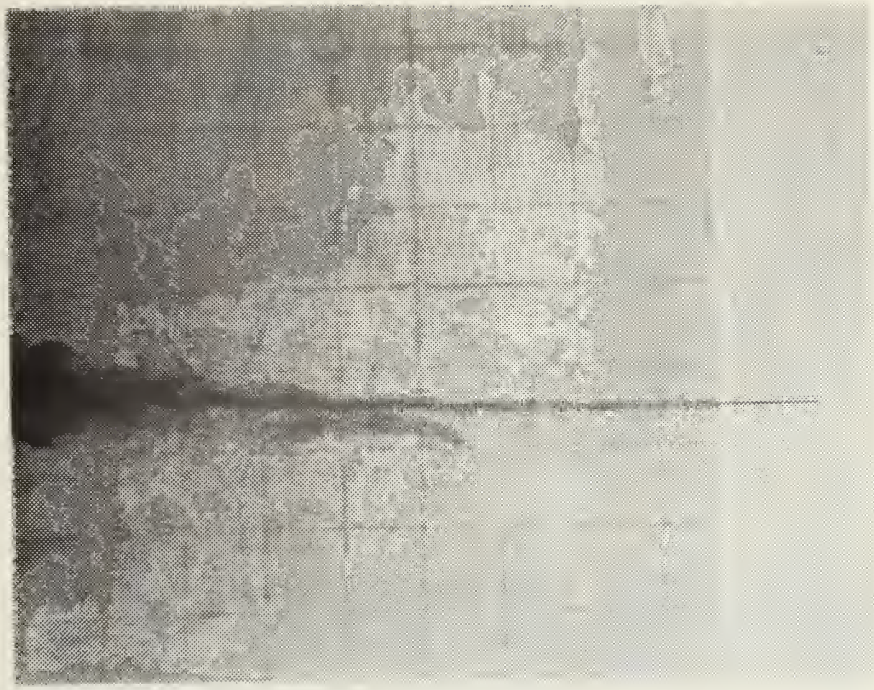
No. 28

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.5" H_2O

ΔT JET:
9°F



Injection:

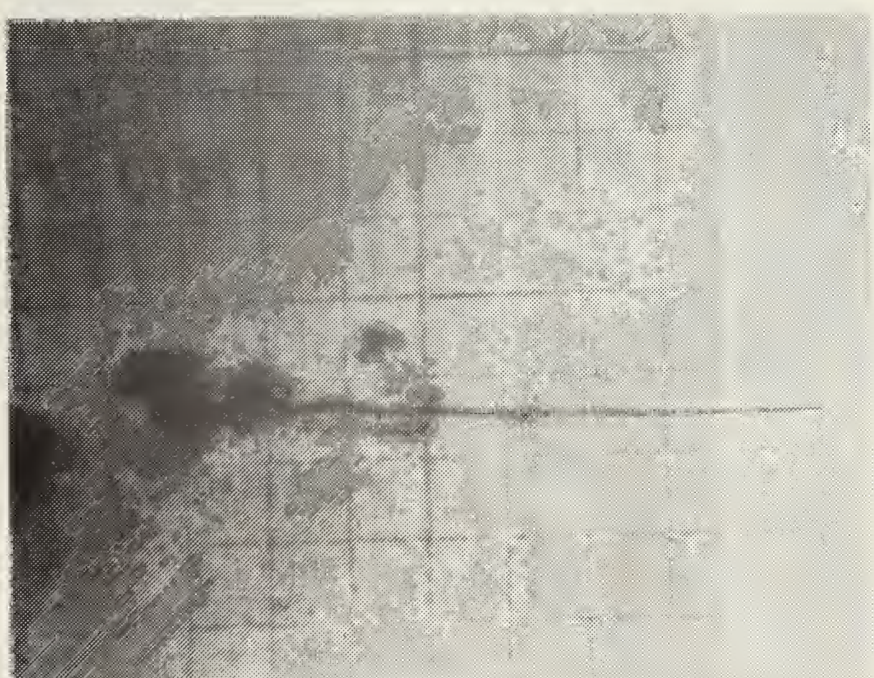
No. 29

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
6°F



Injection:

No. 30

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
6°F

Injection:

No. 31

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.0" H_2O

ΔT JET:
8°F

Injection:

No. 32

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
0.5" H_2O

ΔT JET:
10°F

Injection:

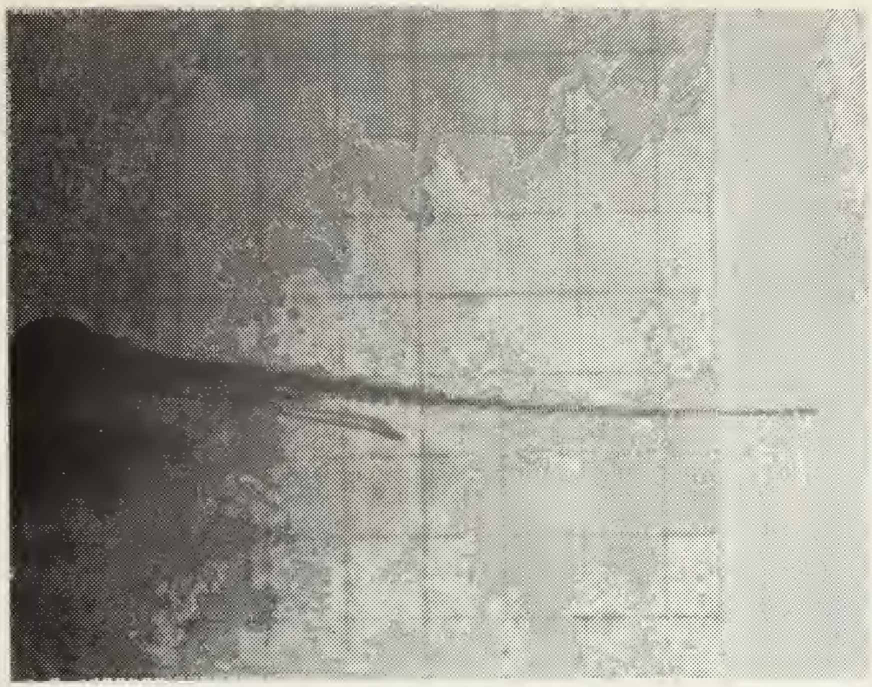
No. 32

VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
0.5" H_2O

ΔT JET:
10°F



Injection:

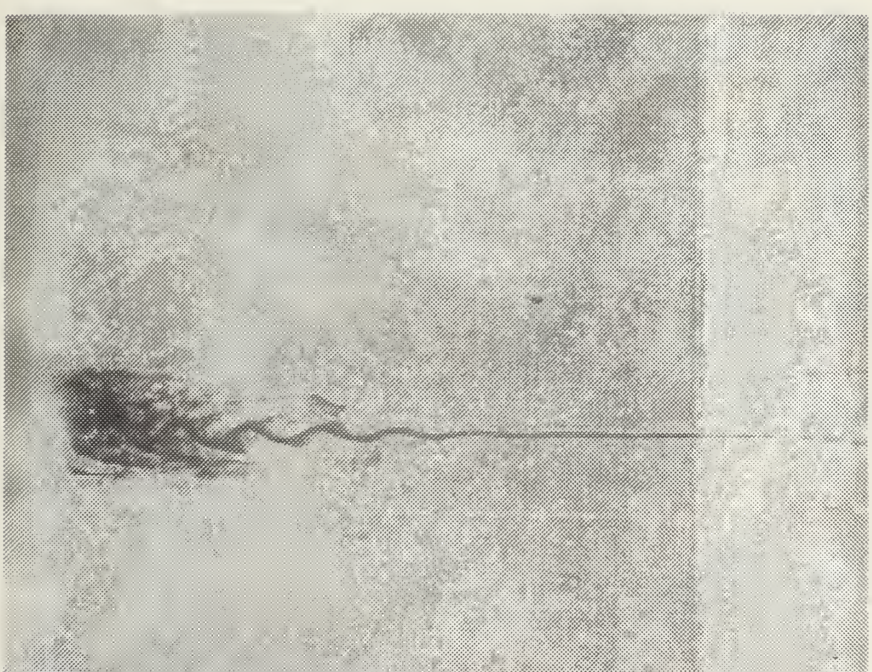
No. 33

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.0" H_2O

ΔT JET:
11°F



Injection:

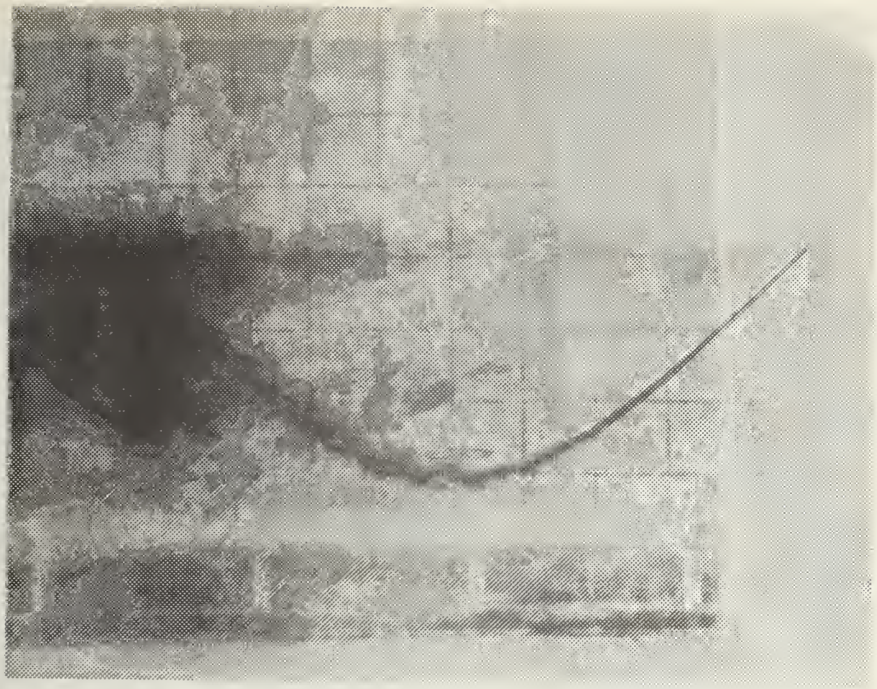
No. 33

VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
1.0" H_2O

ΔT JET:
11°F



Injection:

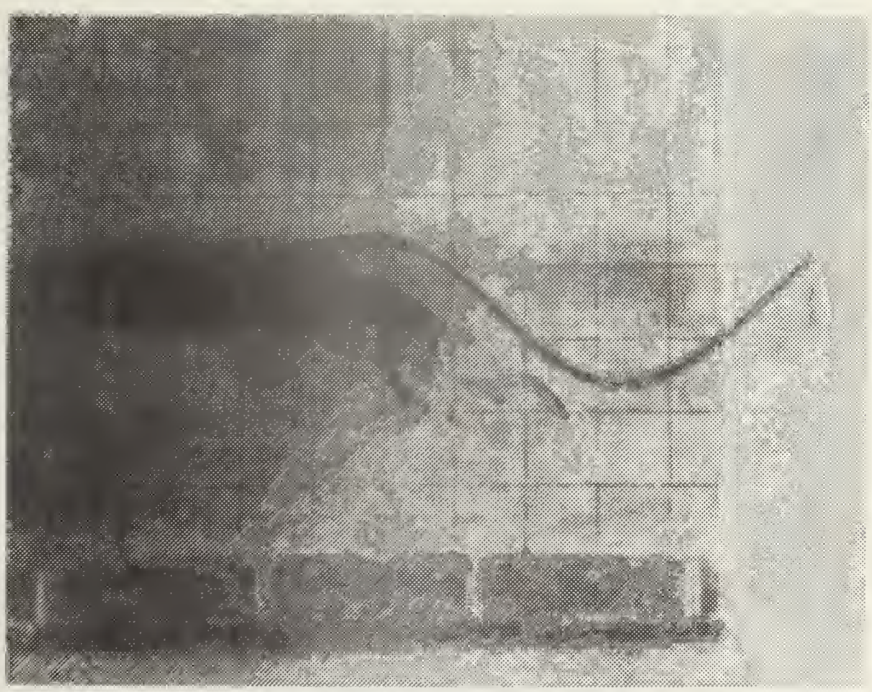
No. 34

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.5" H_2O

ΔT JET:
10°F



Injection:

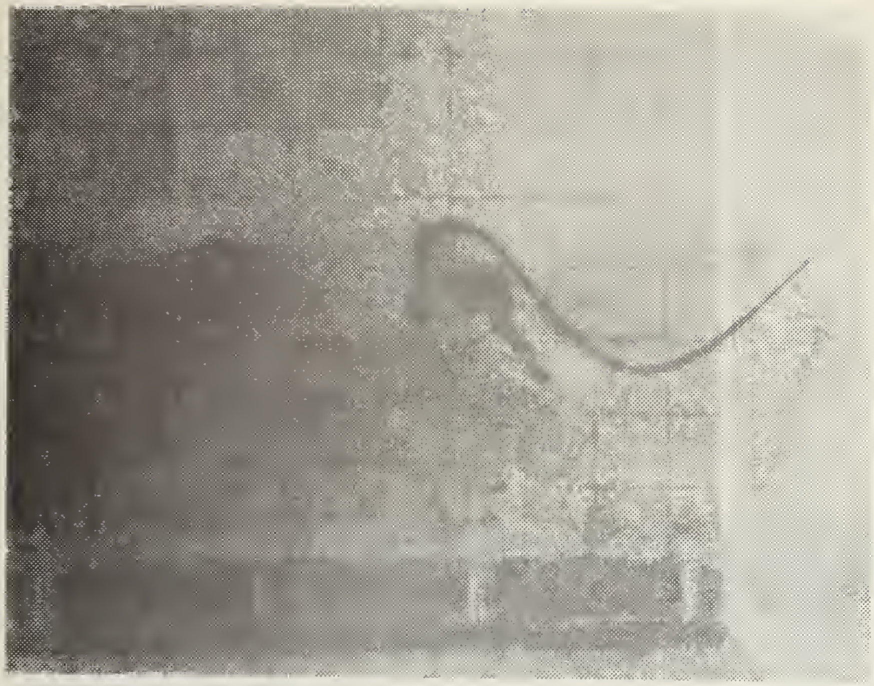
No. 35

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.0" H_2O

ΔT JET:
10°F



Injection:

No. 36

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
0.5" H_2O

ΔT JET:
10°F

Injection:

No. 36

VIEW:
TOP

ANGLE:
DOWN

TOTAL HEAD:
0.5" H_2O

ΔT JET:
10°F

Injection:

No. 37

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
0.5" H_2O

ΔT JET:
10°F

Injection:

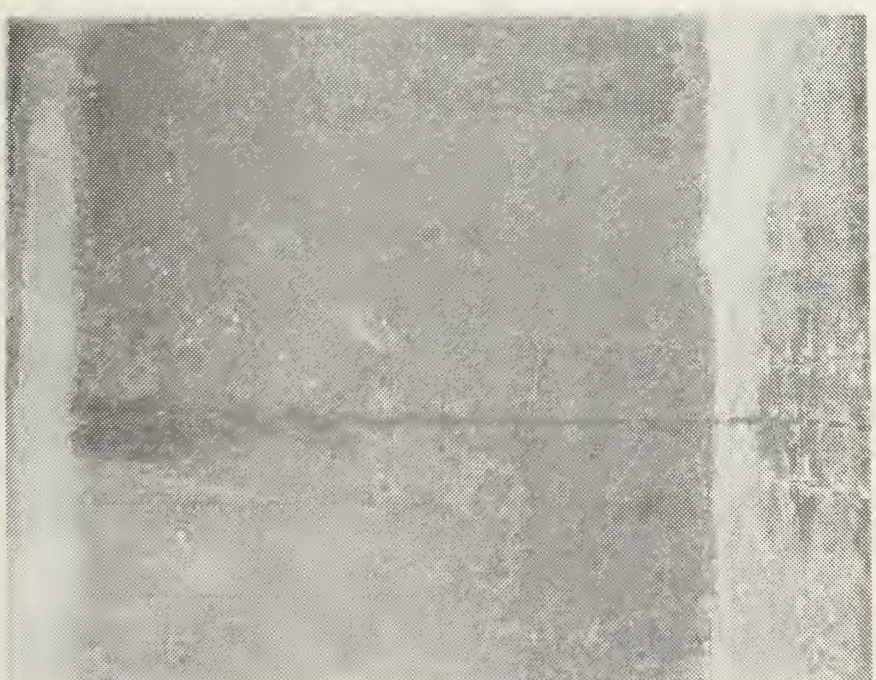
No. 38

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-12°F



Injection:

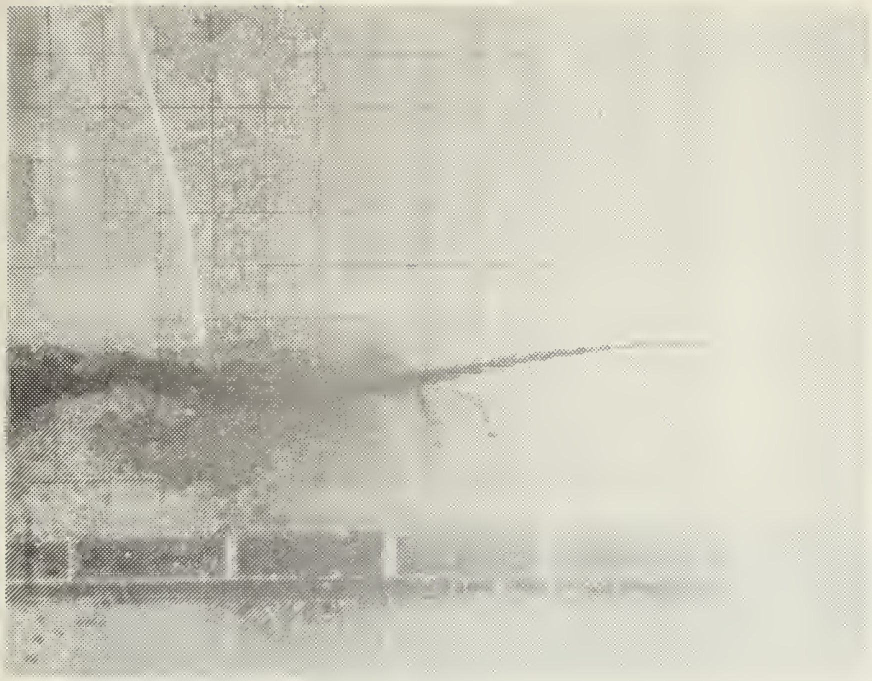
No. 38

VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-12°F



Injection:

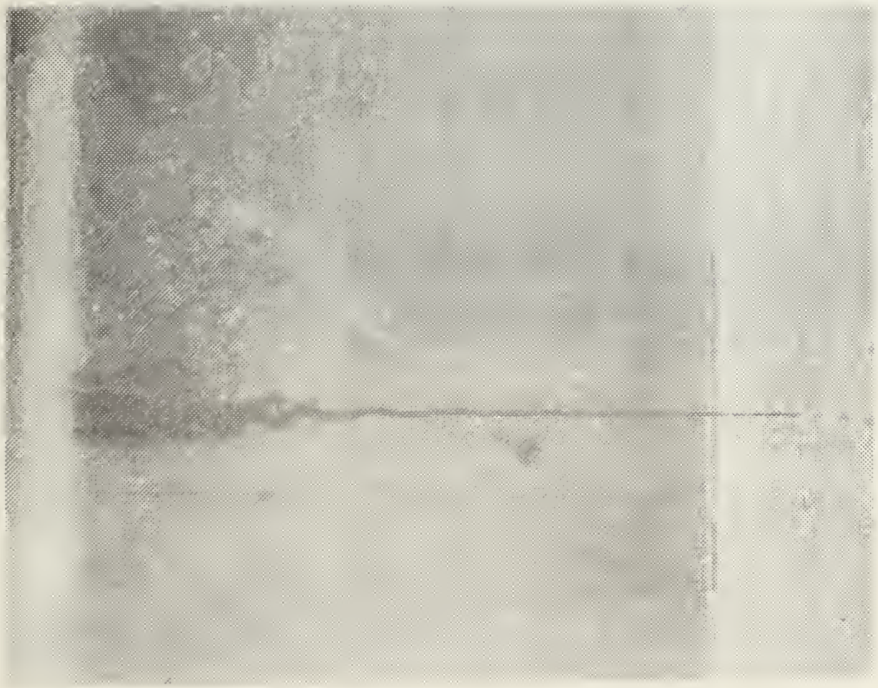
No. 39

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-12°F



Injection:

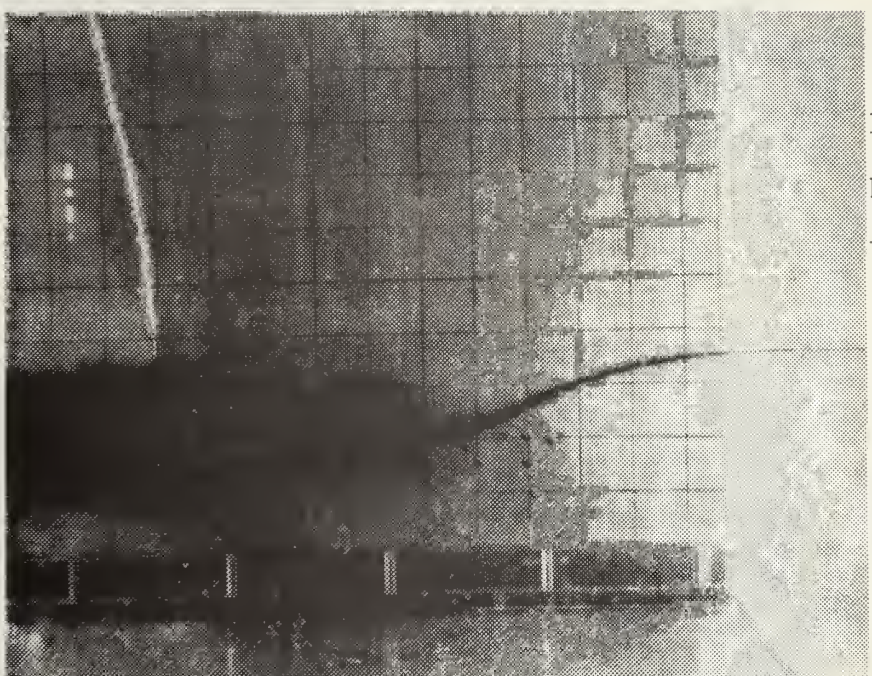
No. 39

VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-12°F



Injection:

No. 40

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.0" H_2O

ΔT JET:
-12°F

Injection:

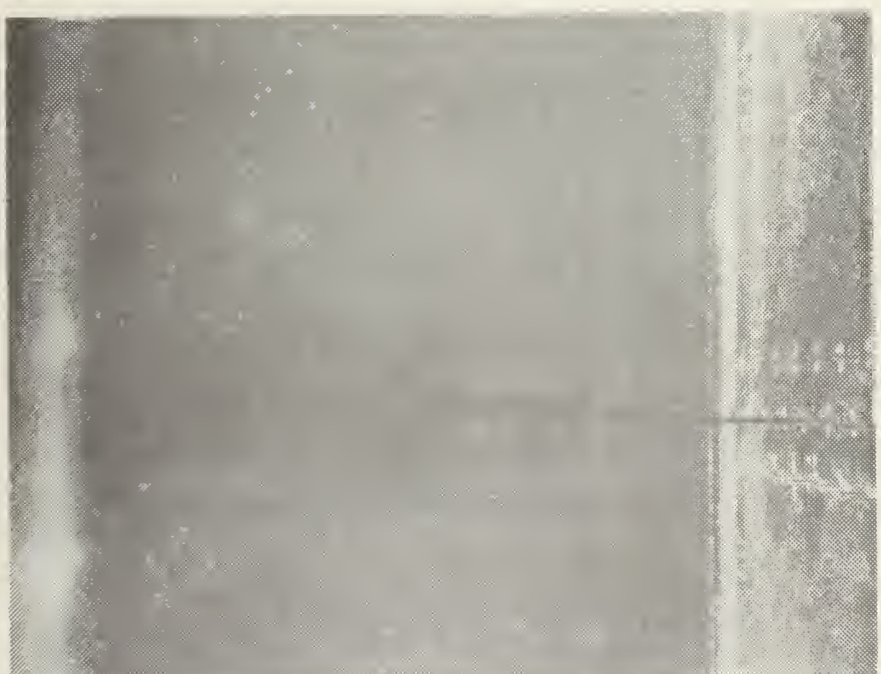
No. 41

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
0.5" H_2O

ΔT JET:
-13°F



Injection:

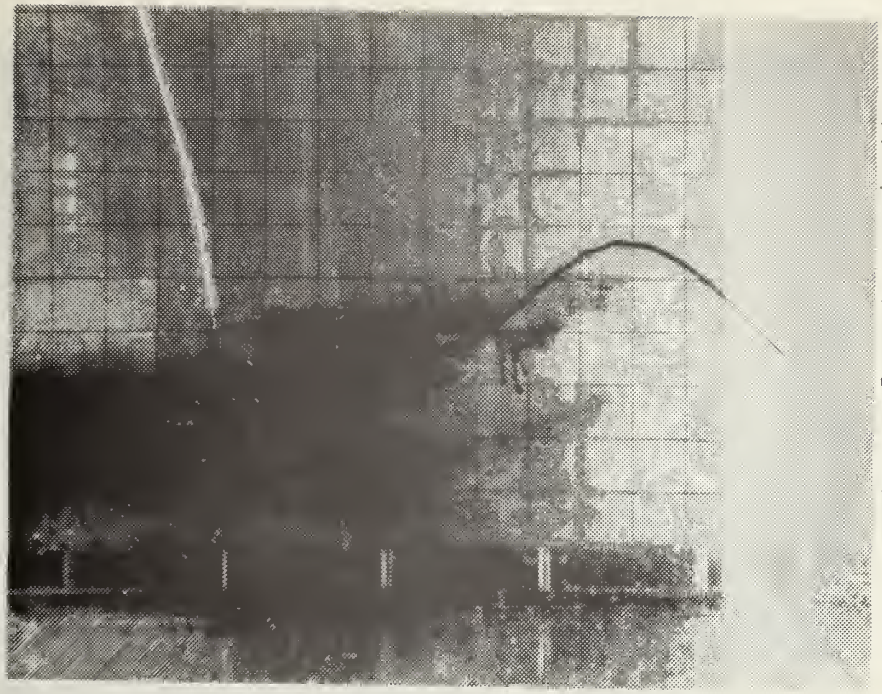
No. 41

VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
0.5" H_2O

ΔT JET:
-13°F



Injection:

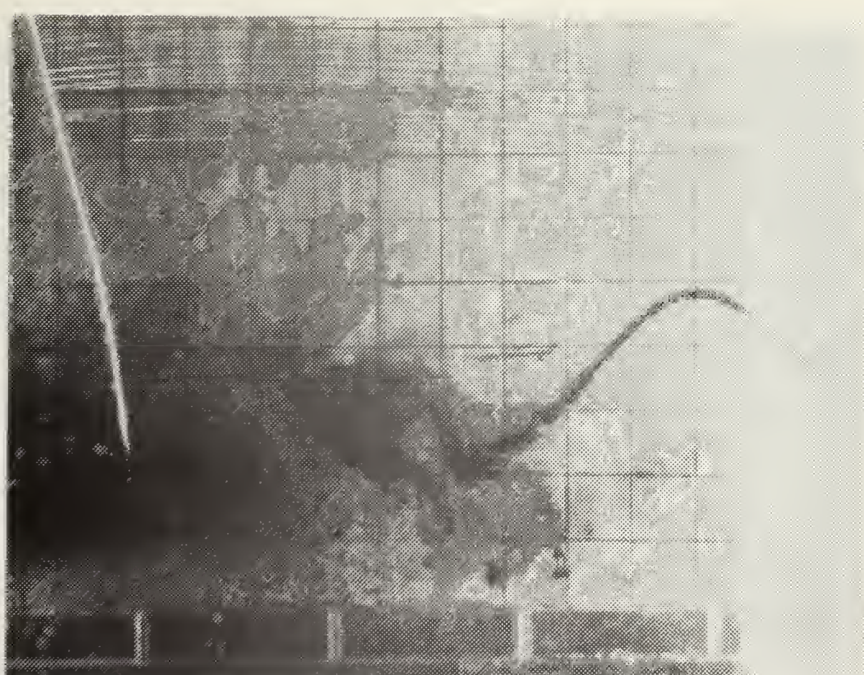
No. 42

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-11°F



Injection:

No. 43

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.0" H_2O

ΔT JET:
-12°F

Injection:

No. 44

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
-14°F

Injection:

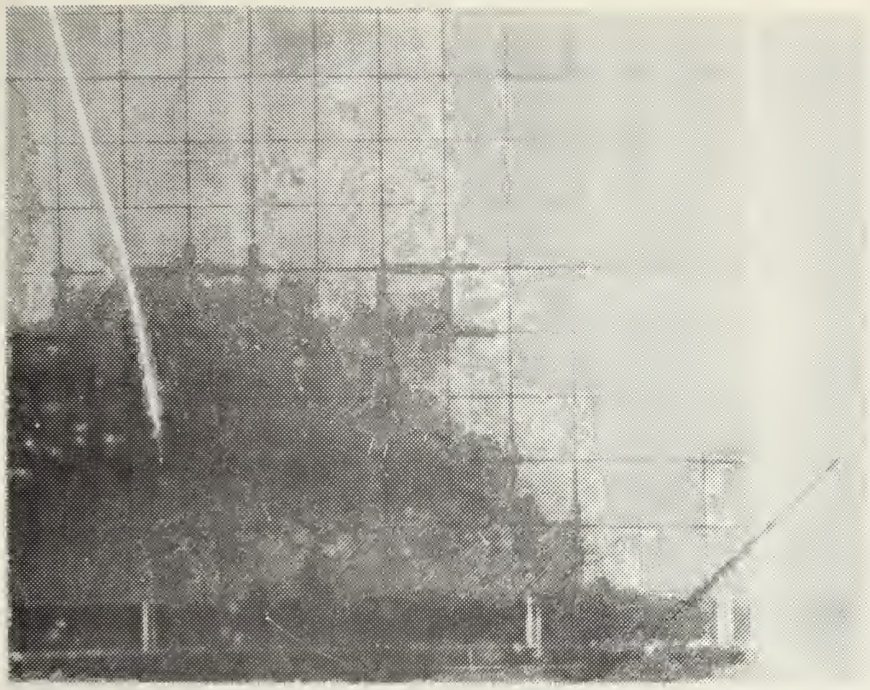
No. 44

VIEW:
TOP

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
-14°F



Injection:

No. 45

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-11°F

Injection:

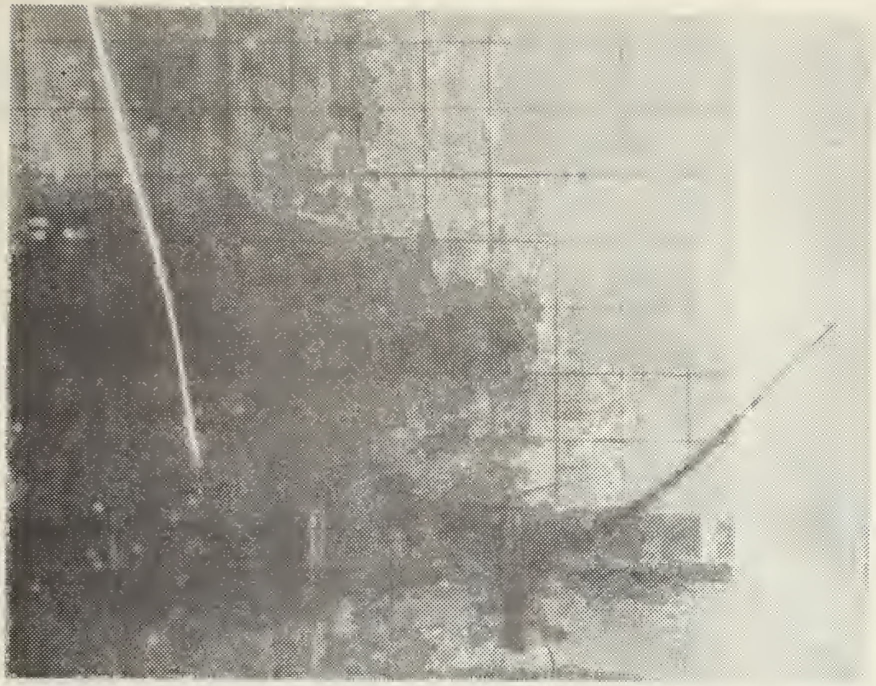
No. 46

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-12°F



Injection:

No. 47

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.0" H_2O

ΔT JET:
-13°F

Injection:

No. 48

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
0.5" H_2O

ΔT JET:
-13°F

Injection:

No. 49

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-20°F

Injection:

No. 51

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-19°F

Injection:

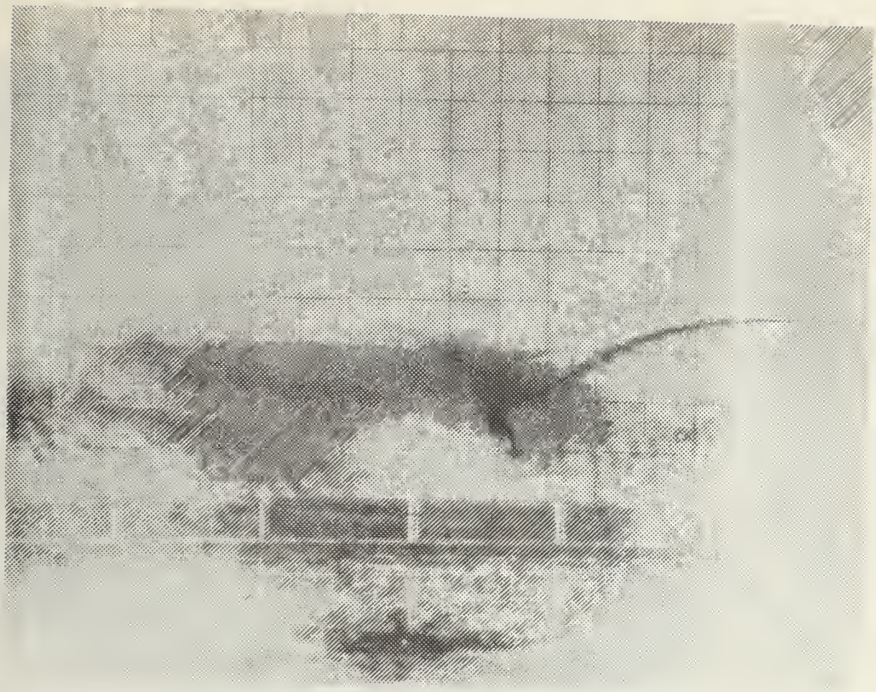
No. 51

VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-19°F



Injection:

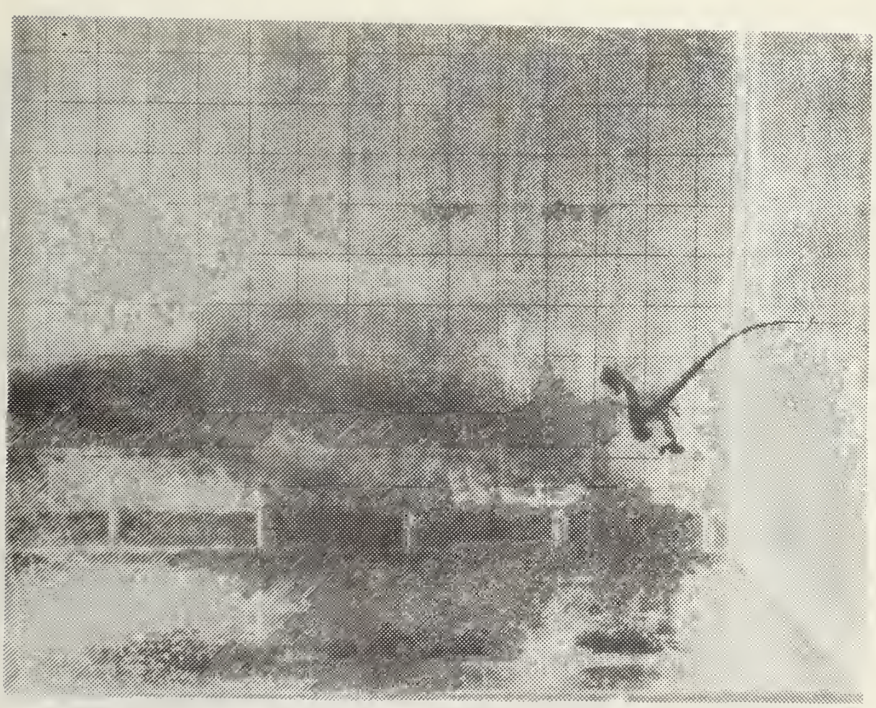
No. 52

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.0" H_2O

ΔT JET:
-19°F



Injection:

No. 53

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
0.5" H_2O

ΔT JET:
-18°F

Injection:

No. 54

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-17°F

Injection:

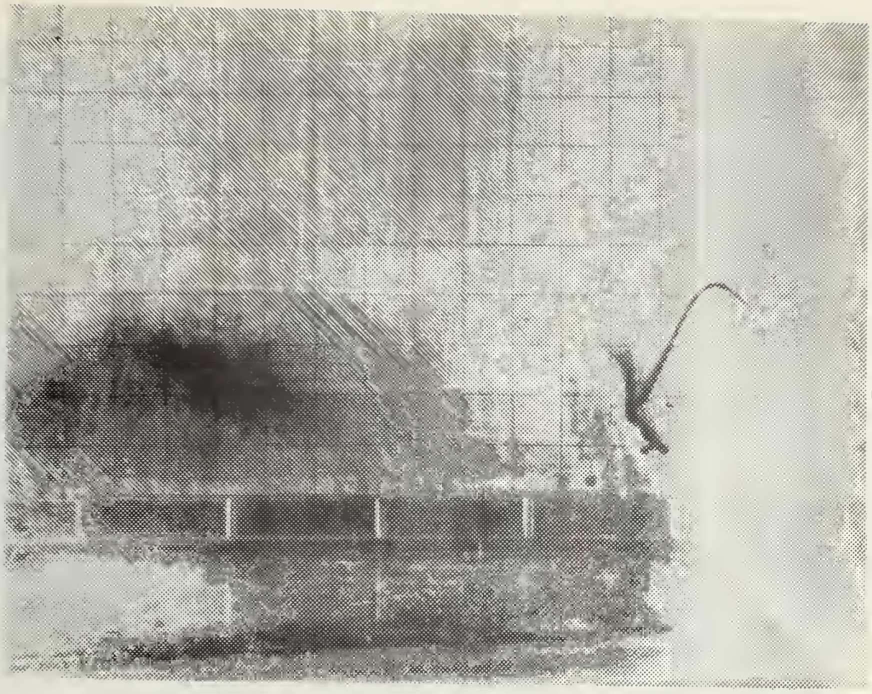
No. 55

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.0" H_2O

ΔT JET:
-17°F



Injection:

No. 56

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
-17°F

Injection:

No. 57

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-5°F

Injection:

No. 58

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.0" H_2O

ΔT JET:
-6°F

Injection:

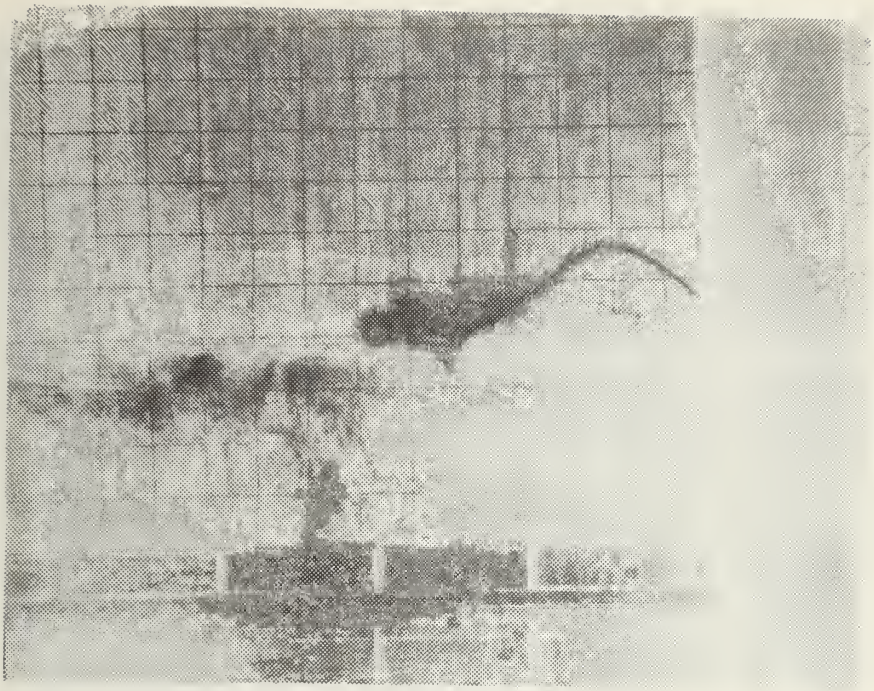
No. 59

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
0.5" H_2O

ΔT JET:
-6°F



Injection:

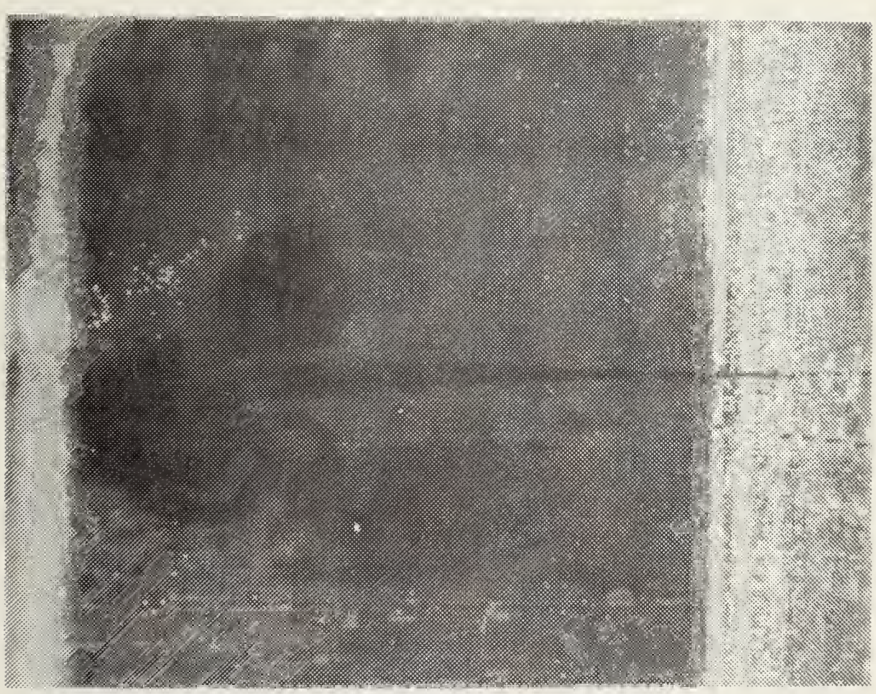
No. 60

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-8°F



Injection:

No. 60

VIEW:
TOP

ANGLE:
UP

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-8°F

Injection:

No. 61

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.0" H_2O

ΔT JET:
-8°F

Injection:

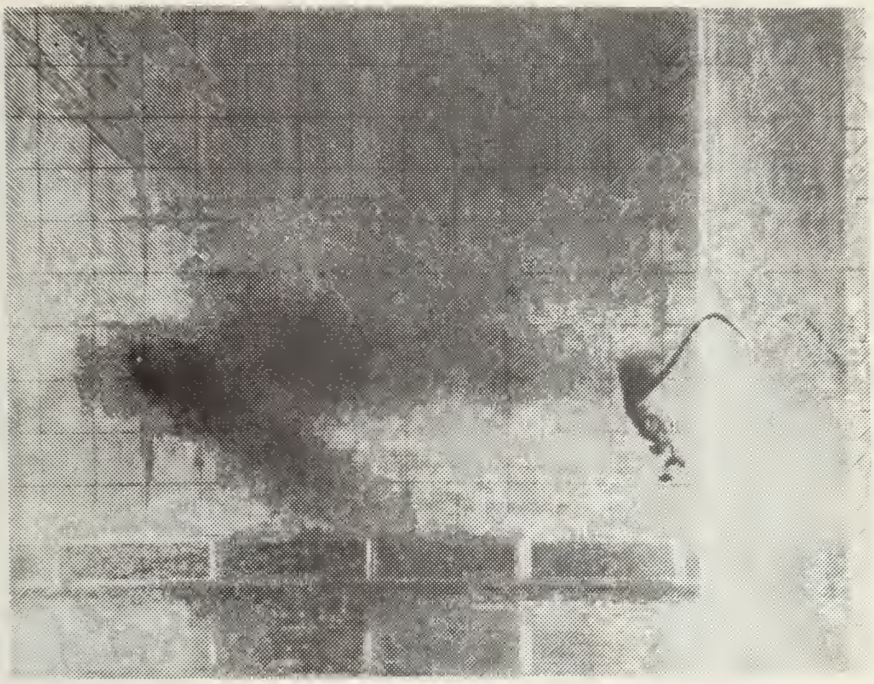
No. 62

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.0" H_2O

ΔT JET:
-8°F



Injection:

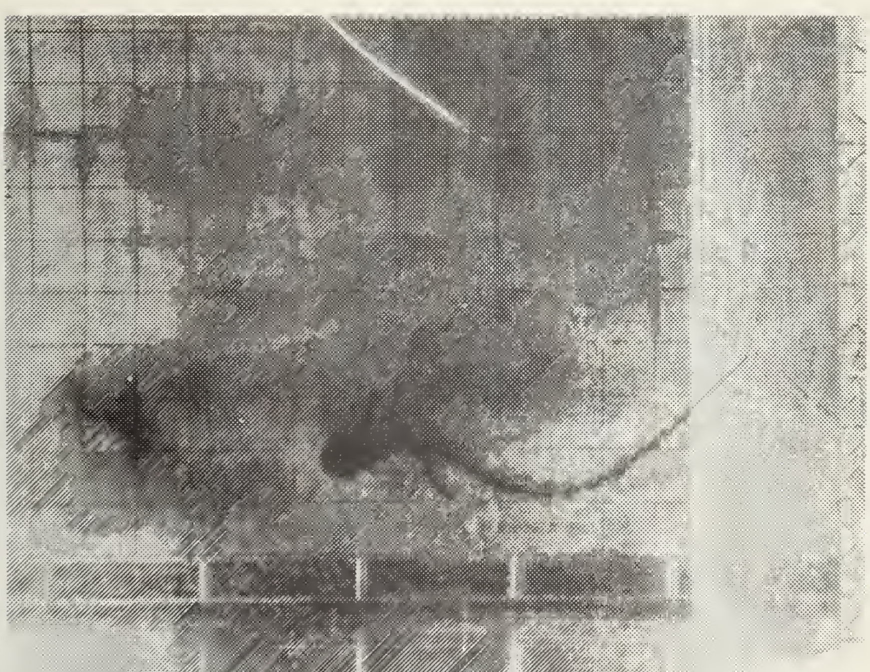
No. 63

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
-8°F



Injection:

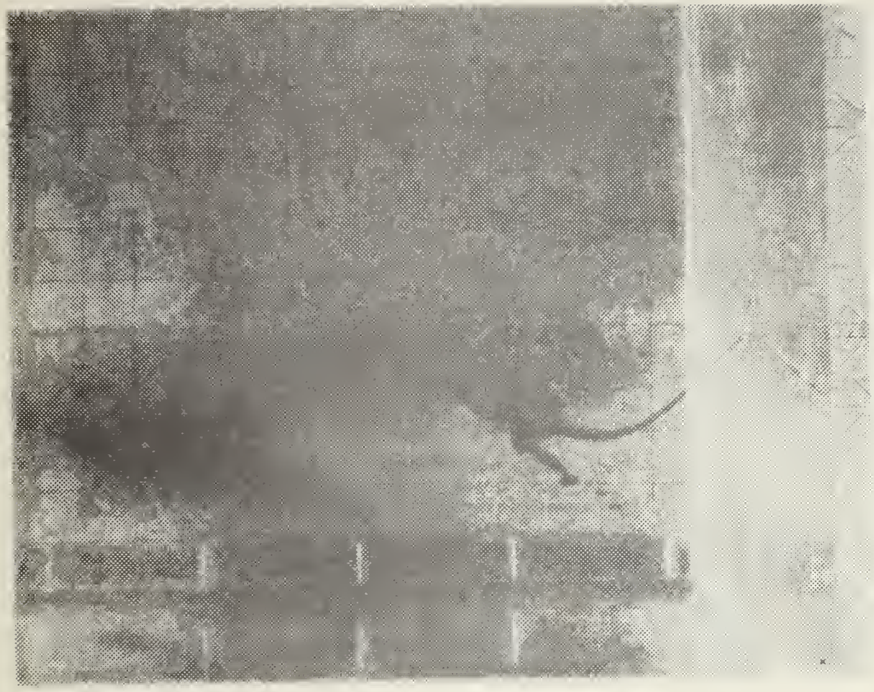
No. 64

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.5" H_2O

ΔT JET:
-5°F



Injection:

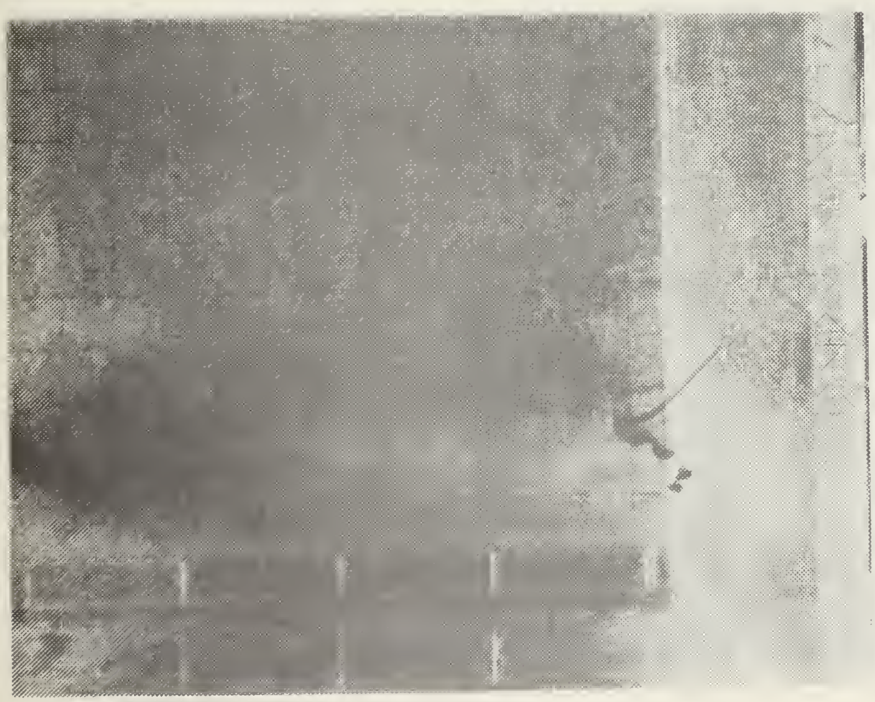
No. 65

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.0" H_2O

ΔT JET:
-6°F



Injection:

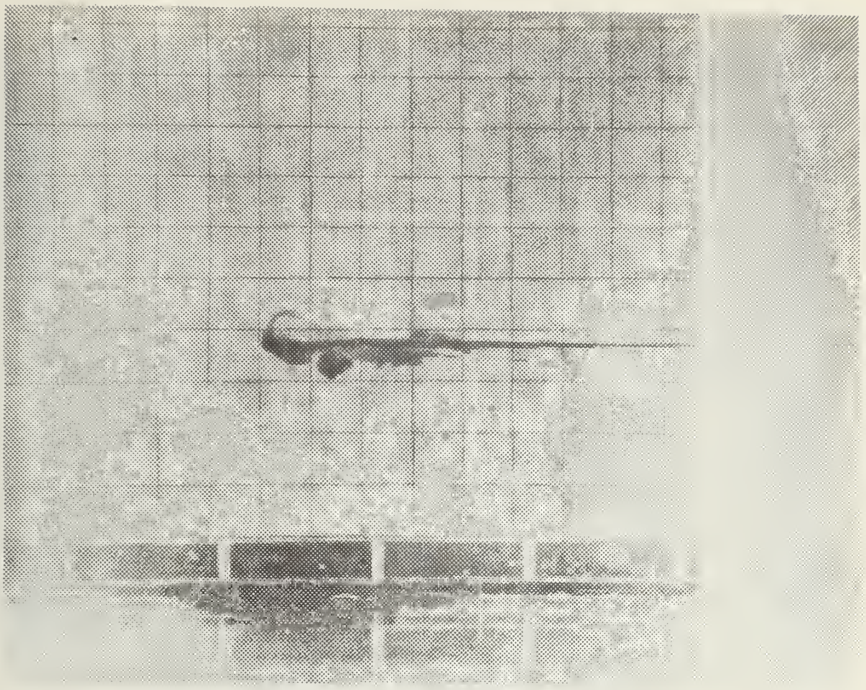
No. 66

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
0.5" H_2O

ΔT JET:
-7°F



Injection:

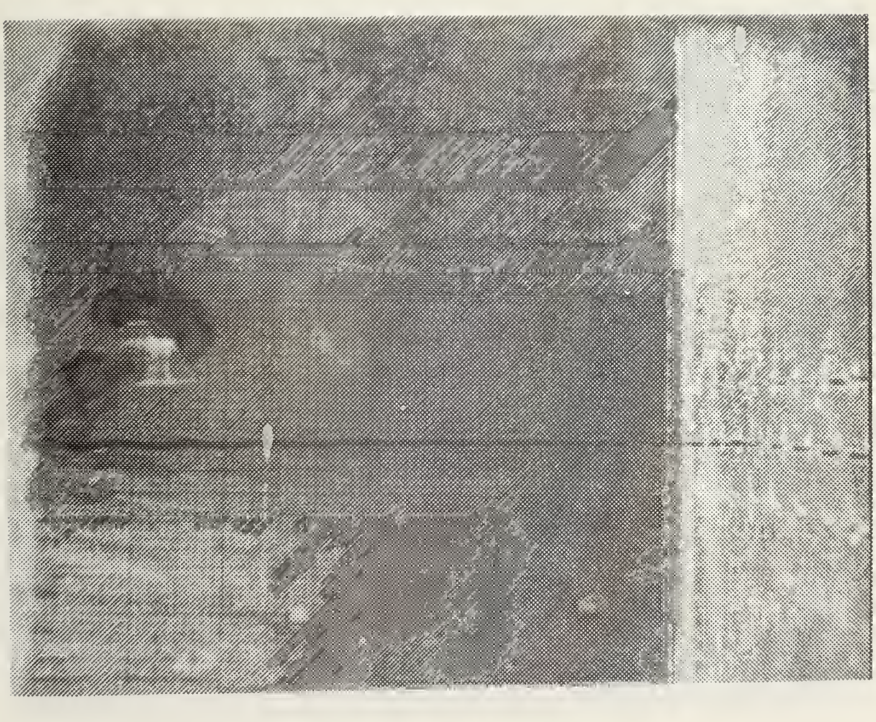
No. 67

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
0°F



Injection:

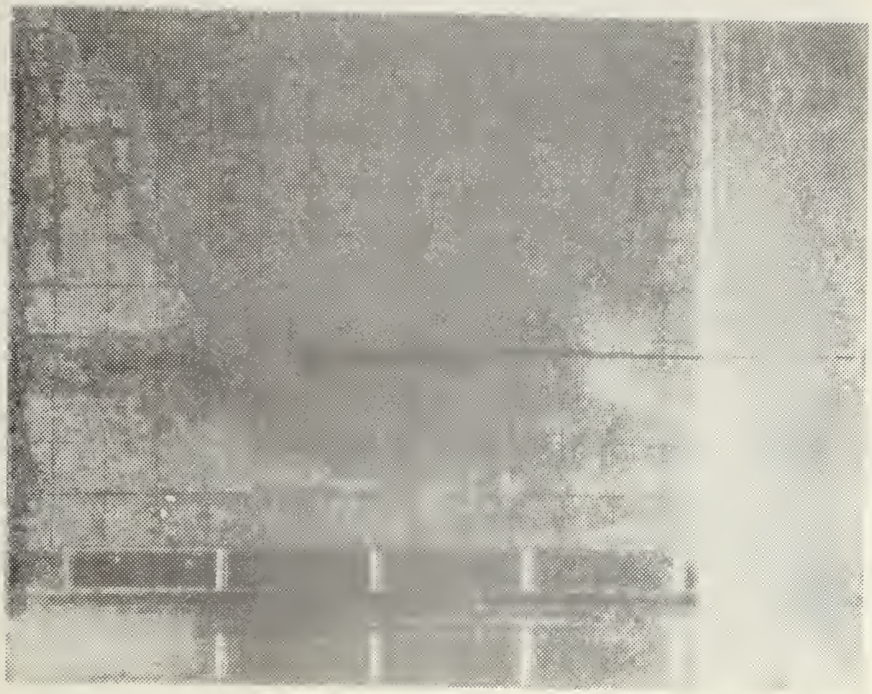
No. 67

VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
0°F



Injection:

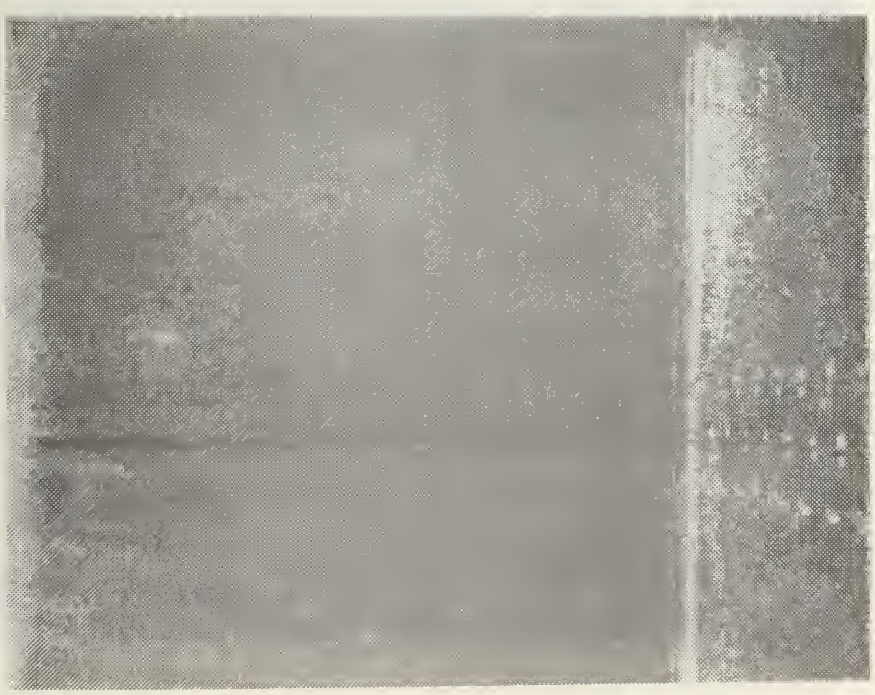
No. 68

VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
1.0" H_2O

ΔT JET:
0°F



Injection:

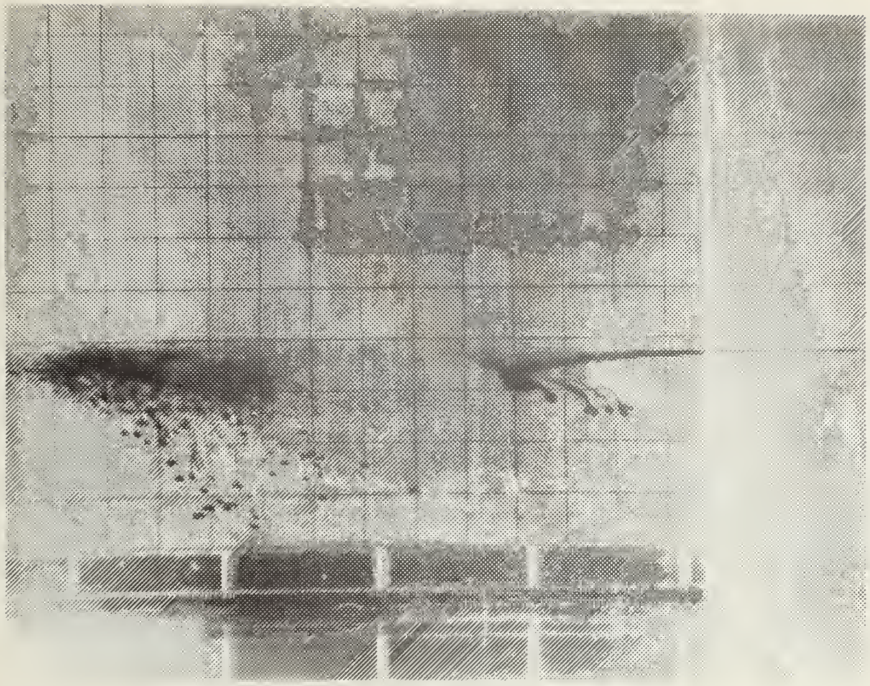
No. 68

VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
1.0" H_2O

ΔT JET:
0°F



Injection:

No. 69

VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
0.5" H_2O

ΔT JET:
-1°F

Injection:

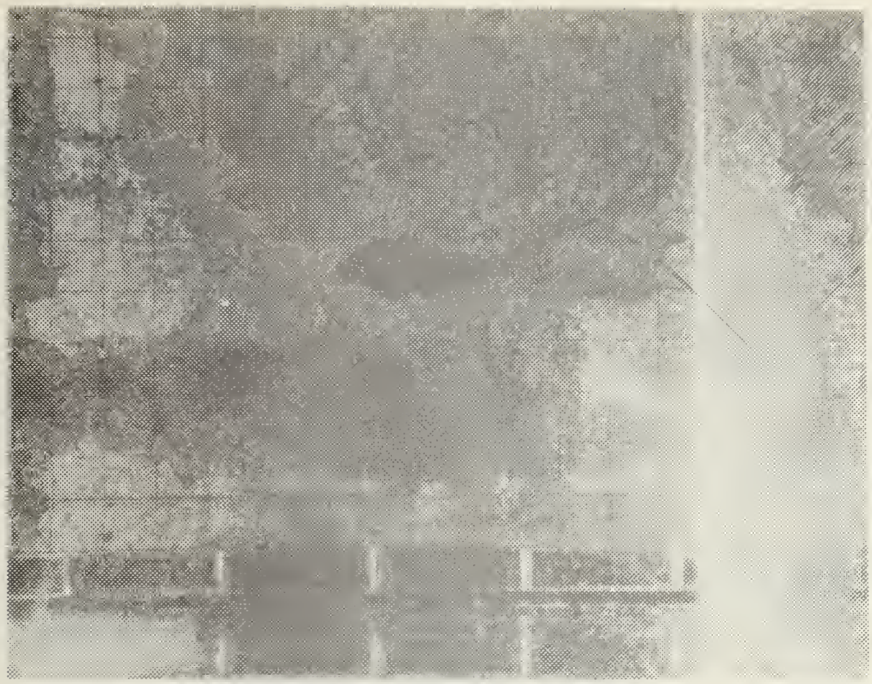
No. 69

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
0.5" H_2O

ΔT JET:
-1°F



Injection:

No. 70

VIEW:
TOP

ANGLE:
UP

TOTAL HEAD:
1.5" H_2O

ΔT JET:
0.5°F

Injection:

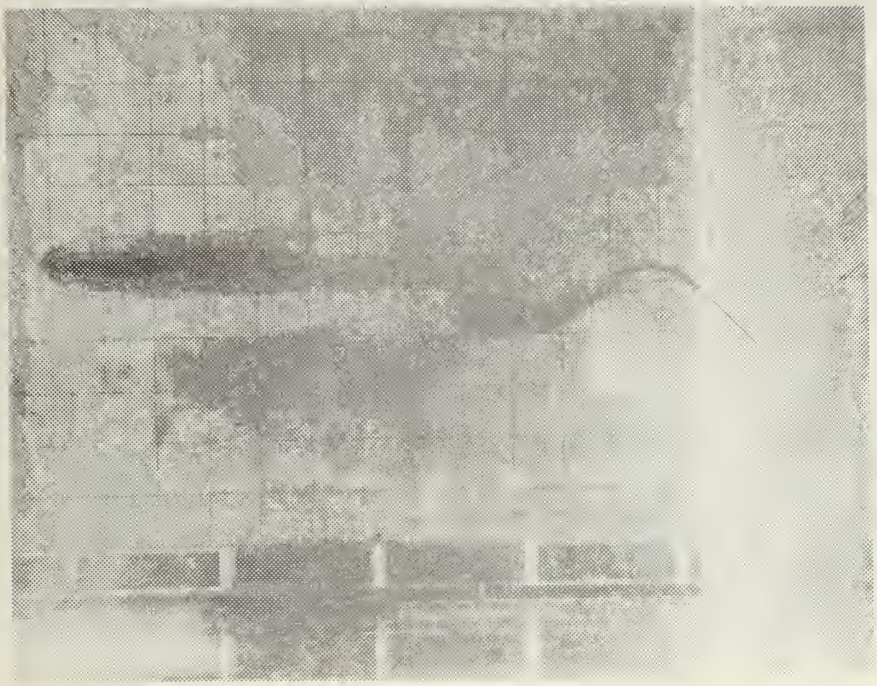
No. 70

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.5" H_2O

ΔT JET:
0.5°F



Injection:

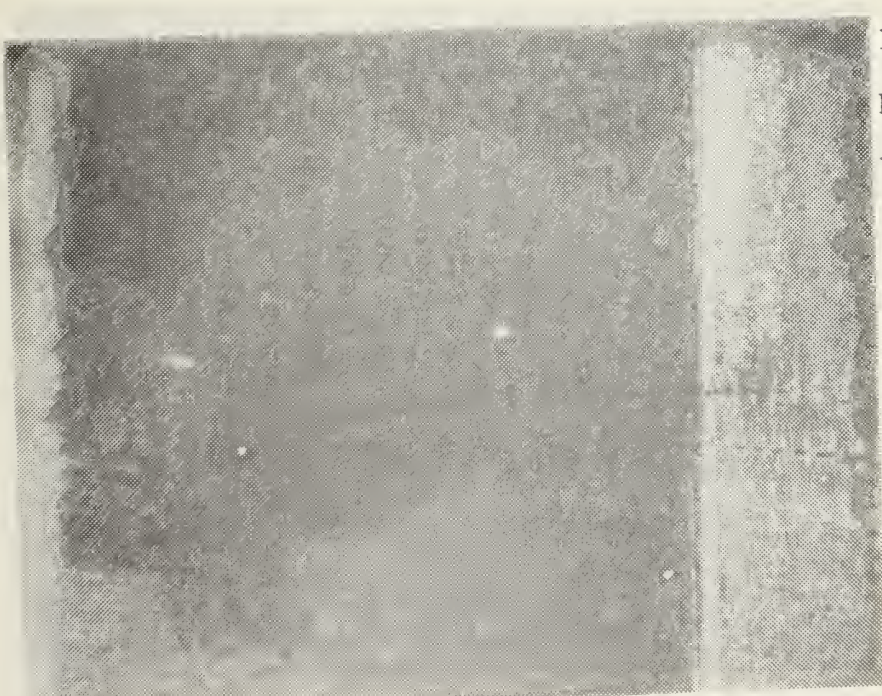
No. 71

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.0" H_2O

ΔT JET:
-0.5°F



Injection:

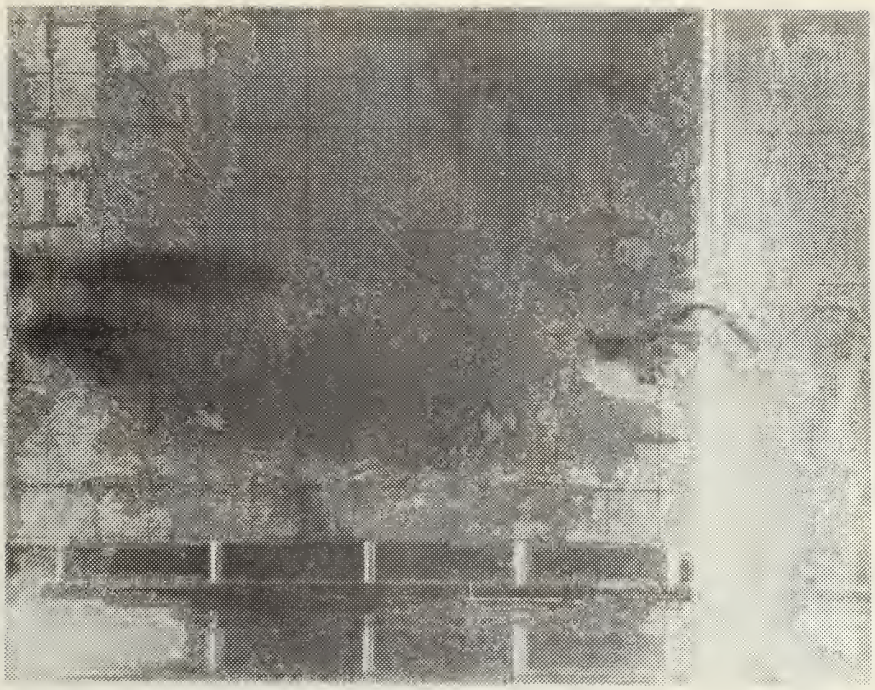
No. 71

VIEW:
TOP

ANGLE:
UP

TOTAL HEAD:
1.0" H_2O

ΔT JET:
-0.5°F



Injection:

No. 72

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
0°F

Injection:

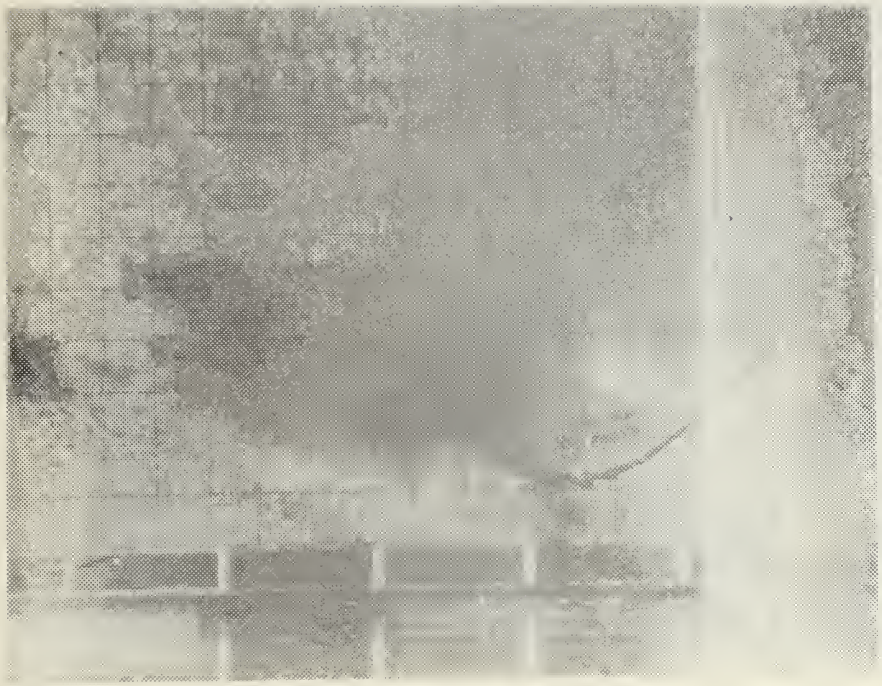
No. 72

VIEW:
TOP

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
0°F



Injection:

No. 73

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.5" H_2O

ΔT JET:
0°F

Injection:

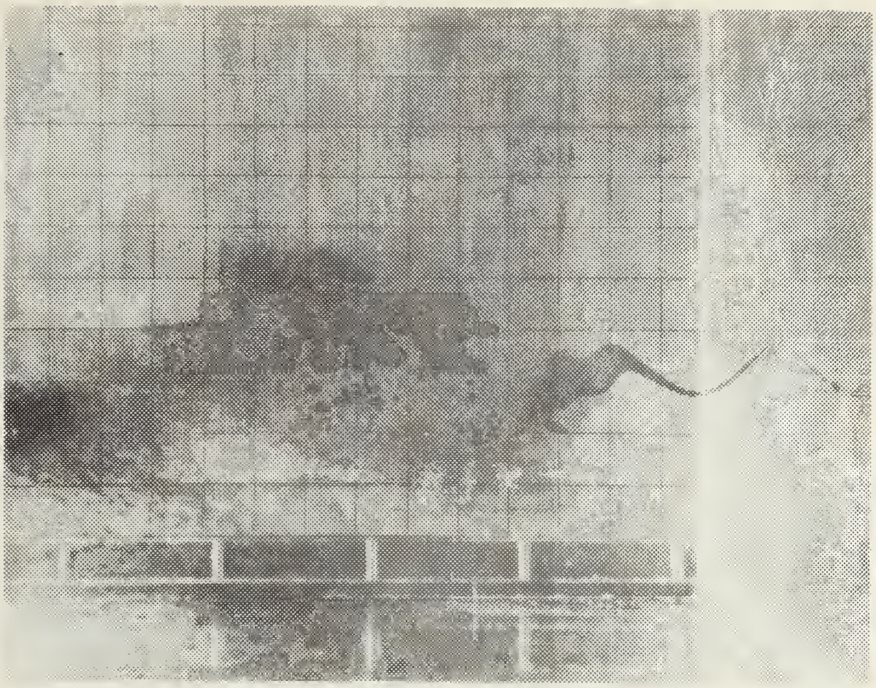
No. 73

VIEW:
TOP

ANGLE:
DOWN

TOTAL HEAD:
1.5" H_2O

ΔT JET:
0°F



Injection:

No. 75

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
0.5" H_2O

ΔT JET:
-0.5°F

Injection:

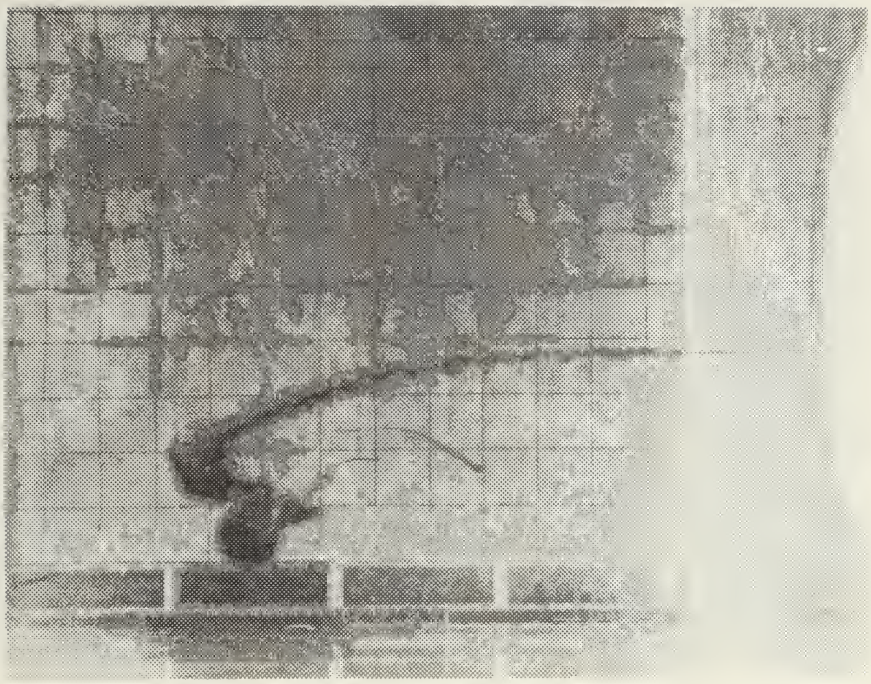
No. 75

VIEW:
TOP

ANGLE:
DOWN

TOTAL HEAD:
0.5" H_2O

ΔT JET:
-0.5°F



Injection:

No. 76

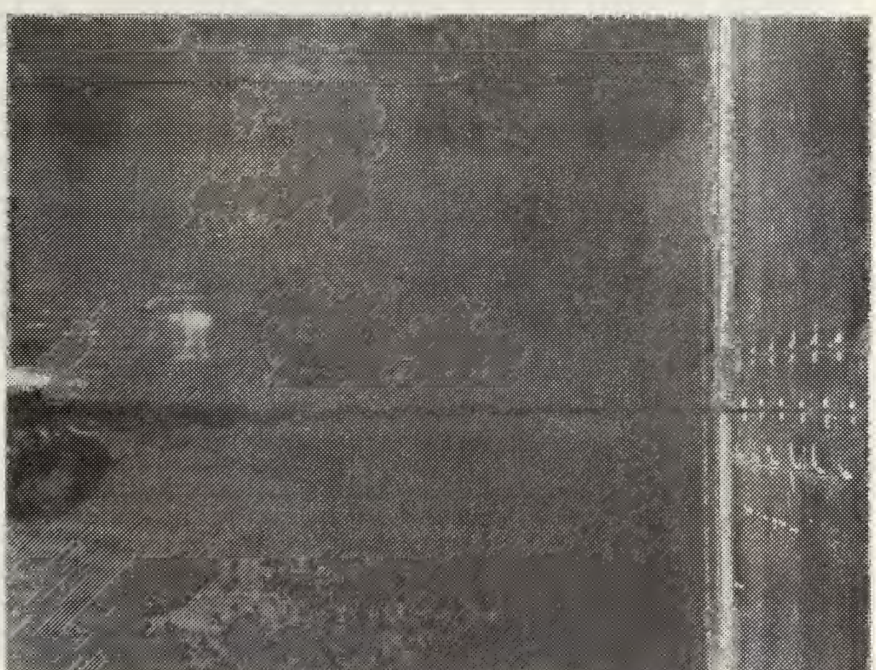
VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
0°F

Uniform Bath



Injection:

No. 76

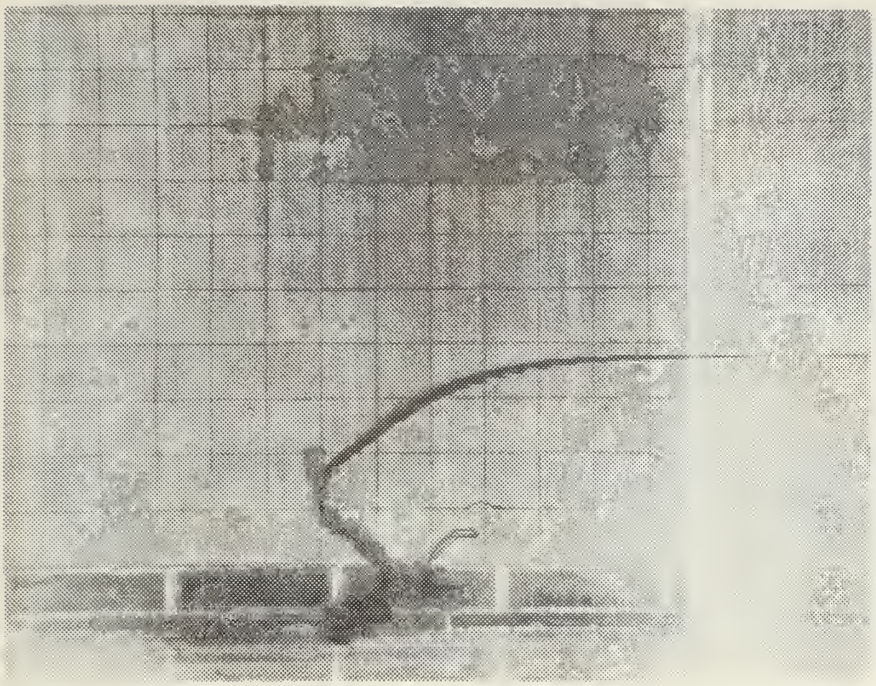
VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
1.5" H_2O

ΔT JET:
0°F

Uniform Bath



Injection:

No. 77

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
1.0" H_2O

ΔT JET:
0°F

Uniform Bath

Injection:

No. 77

VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
1.0" H_2O

ΔT JET:
0°F

Uniform Bath

Injection:

No. 78

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
0.5" H_2O

ΔT JET:
0°F

Uniform Bath

Injection:

No. 78

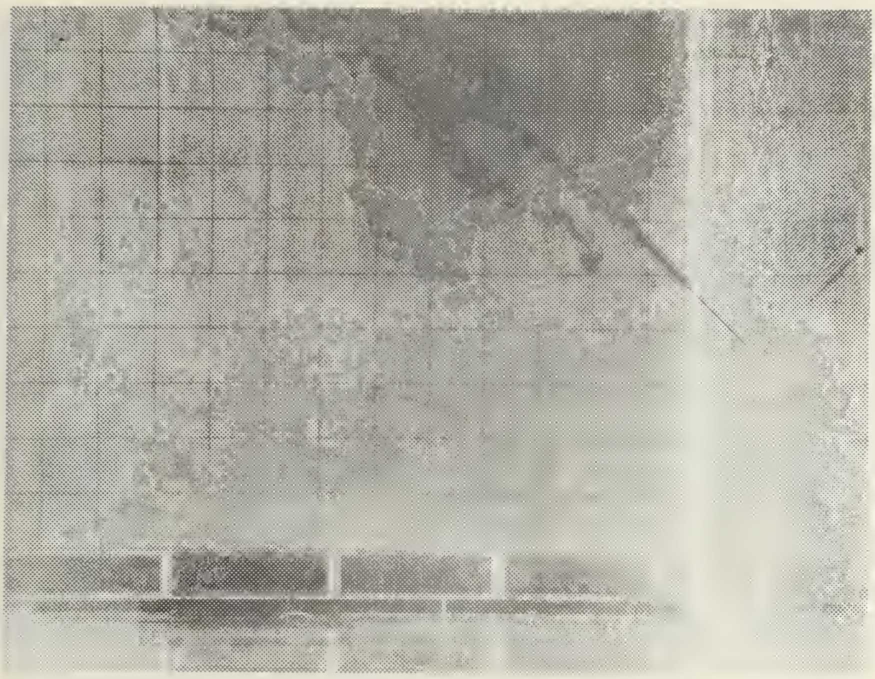
VIEW:
TOP

ANGLE:
STRAIGHT

TOTAL HEAD:
0.5" H_2O

ΔT JET:
0°F

Uniform Bath



Injection:

No. 79

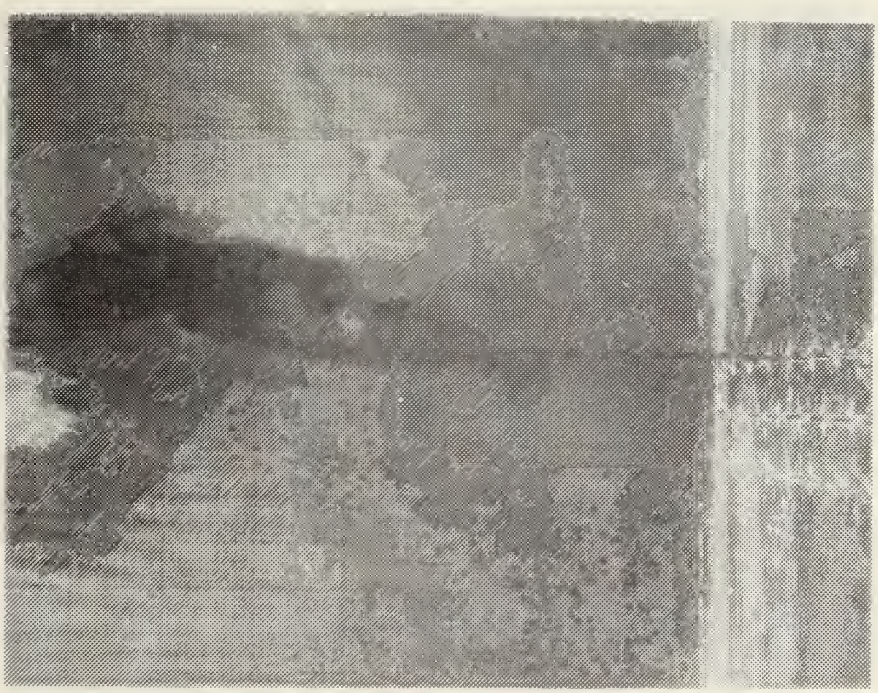
VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.5" H_2O

ΔT JET:
0°F

Uniform Bath



Injection:

No. 79

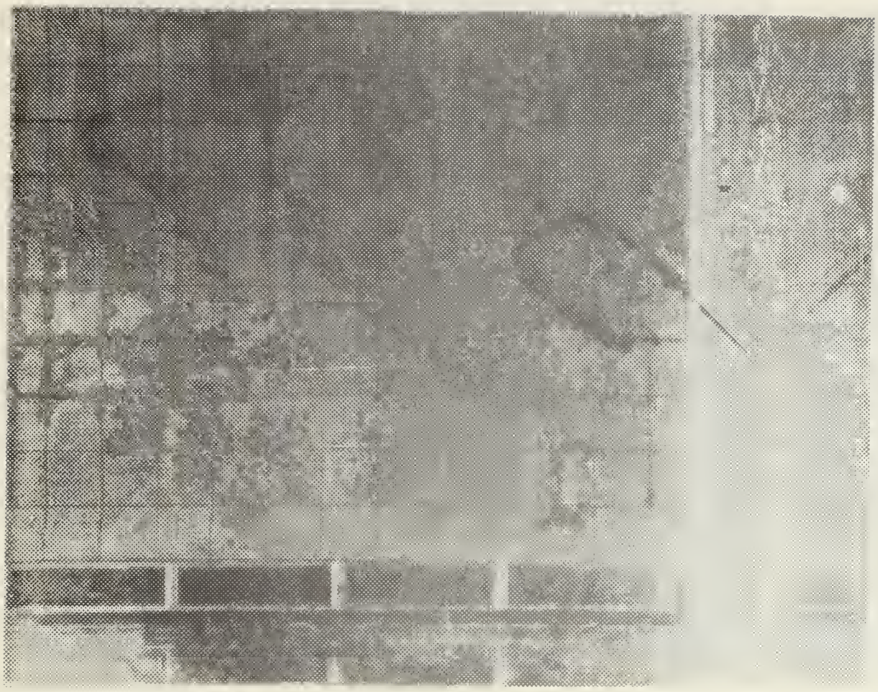
VIEW:
TOP

ANGLE:
UP

TOTAL HEAD:
1.5" H_2O

ΔT JET:
0°F

Uniform Bath



Injection:

No. 80

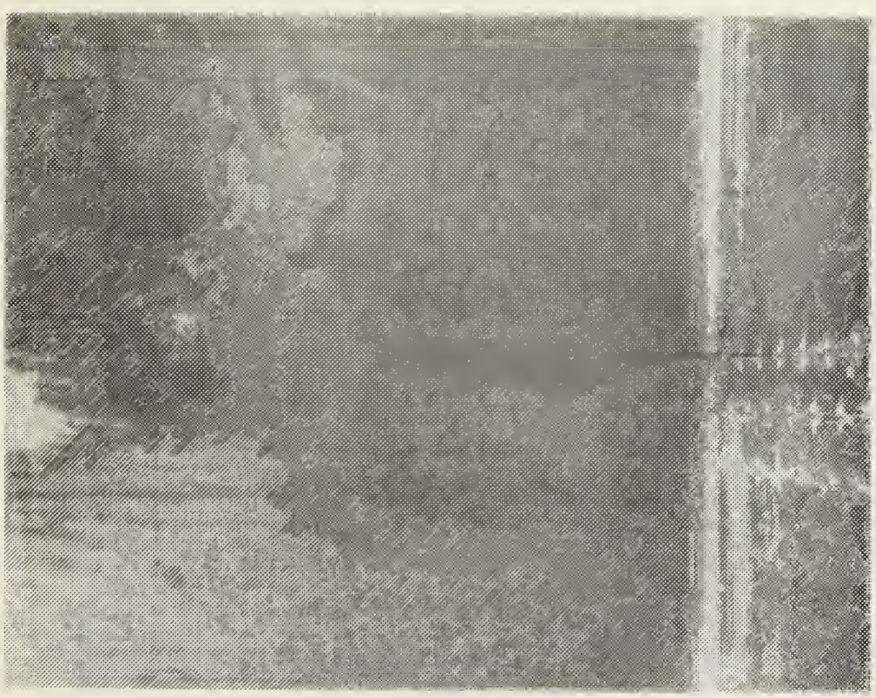
VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.0" H_2O

ΔT JET:
0°F

Uniform Bath



Injection:

No. 80

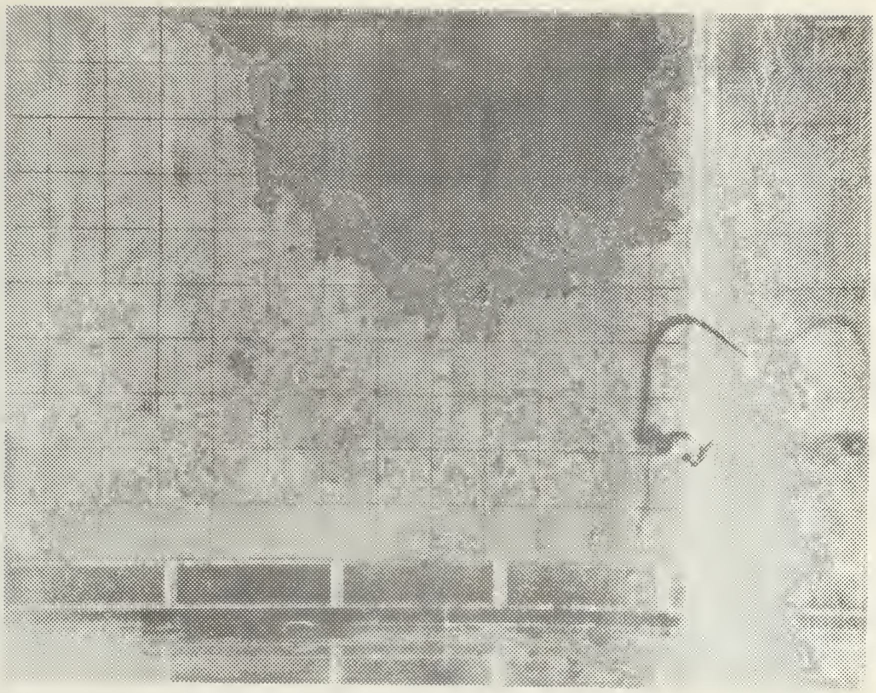
VIEW:
TOP

ANGLE:
UP

TOTAL HEAD:
1.0" H_2O

ΔT JET:
0°F

Uniform Bath



Injection:

No. 81

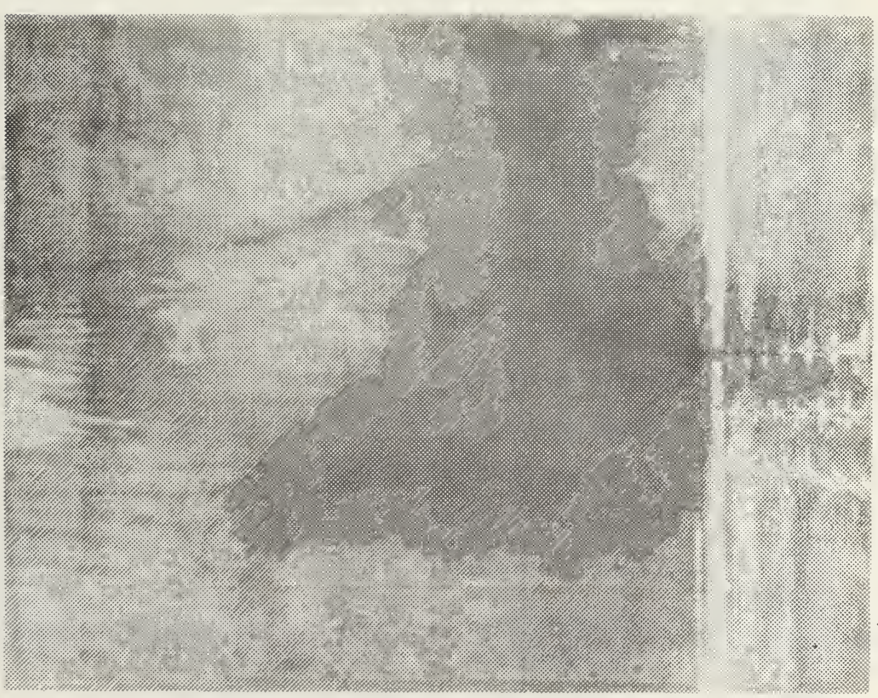
VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
0°F

Uniform Bath



Injection:

No. 81

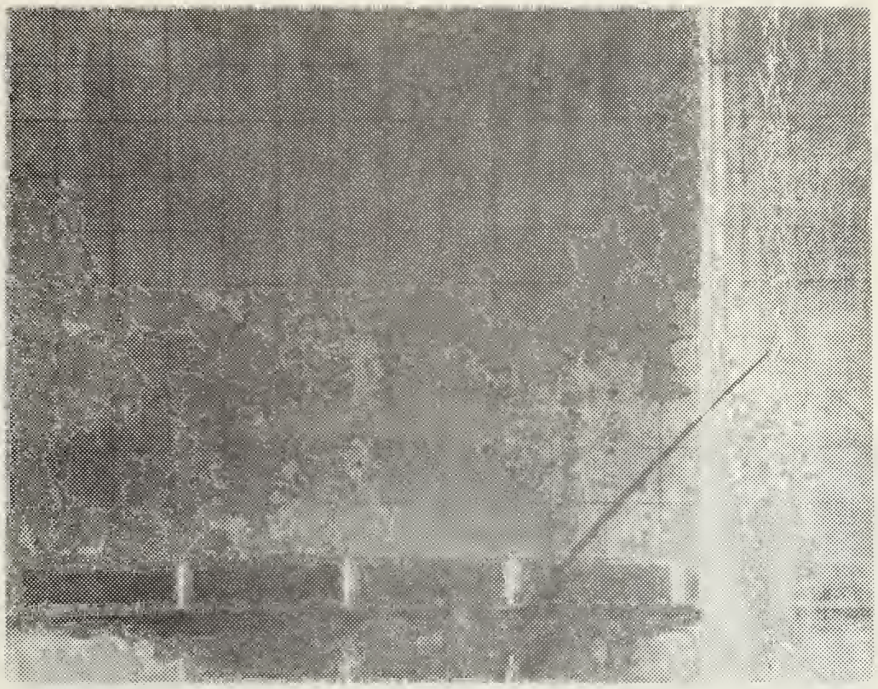
VIEW:
TOP

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
0°F

Uniform Bath



Injection:

No. 82

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.5" H_2O

ΔT JET:
0°F

Uniform Bath

Injection:

No. 83

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.0" H_2O

ΔT JET:
0°F

Uniform Bath

Injection:

No. 84

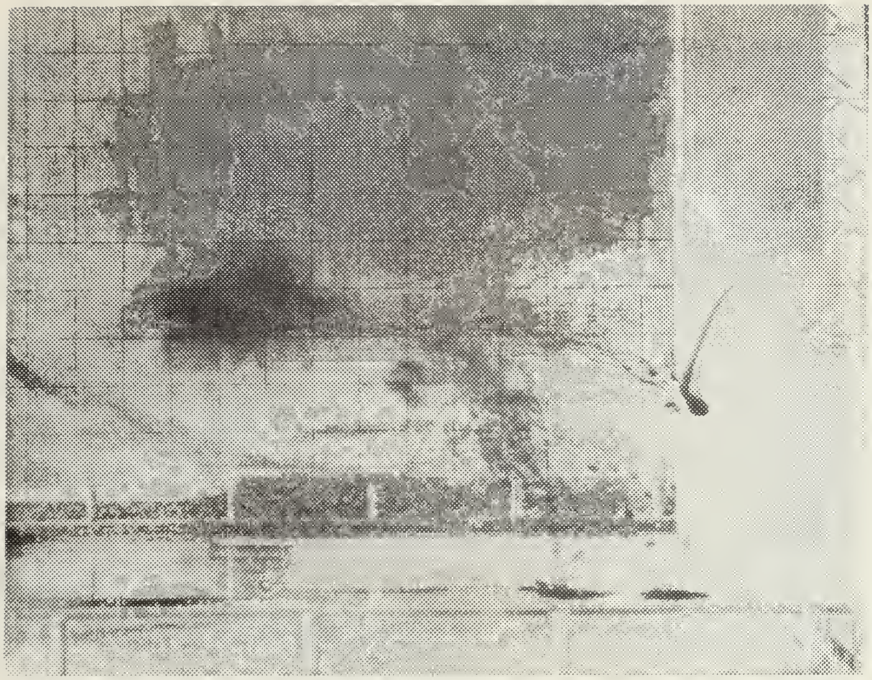
VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
0.5" H_2O

ΔT JET:
0°F

Uniform Bath



Injection:

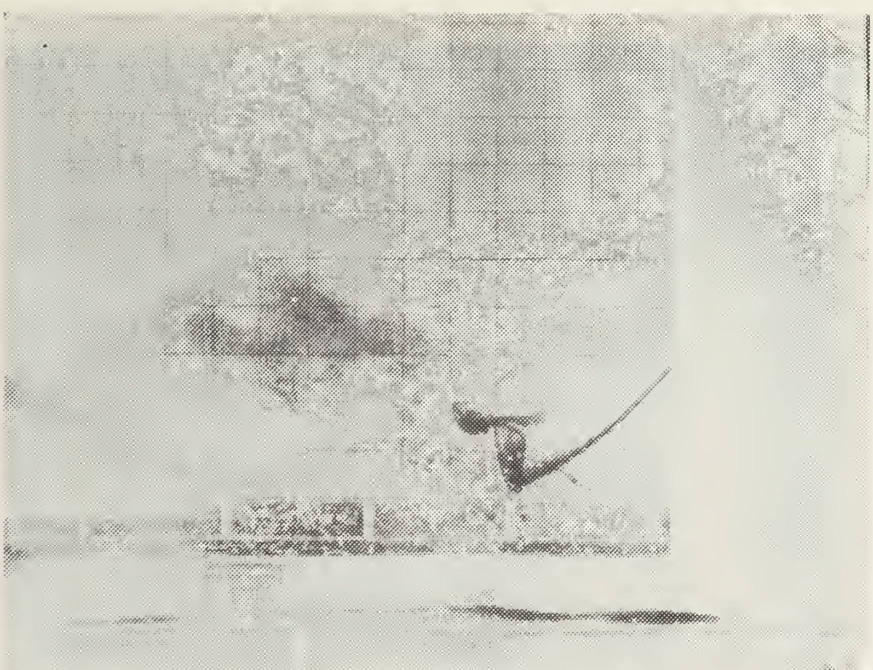
No. 88

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
0.5" H_2O

ΔT JET:
17°F



Injection:

No. 89

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.5" H_2O

ΔT JET:
17°F

Injection:

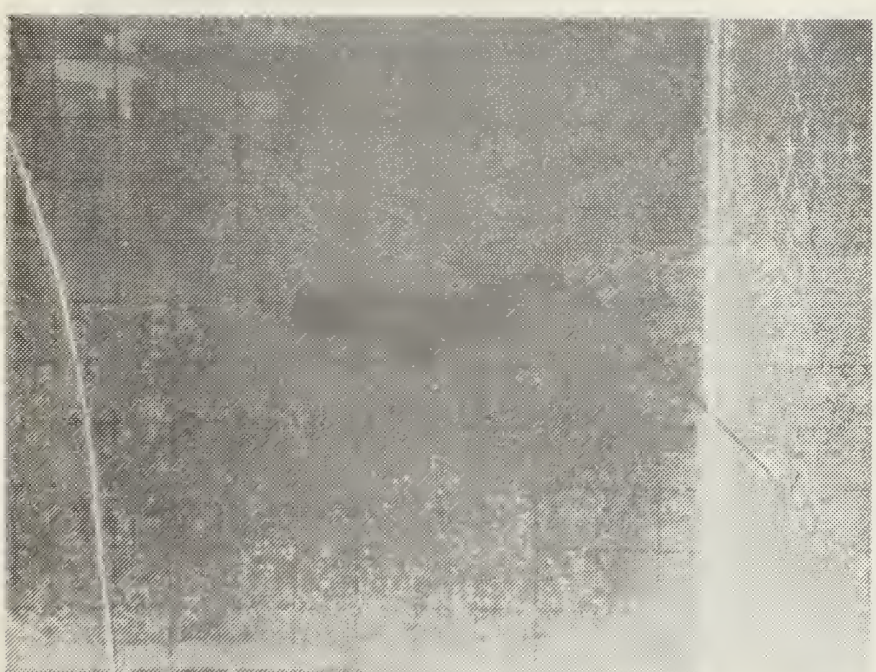
No. 91

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
1.0" H_2O

ΔT JET:
15°F



Injection:

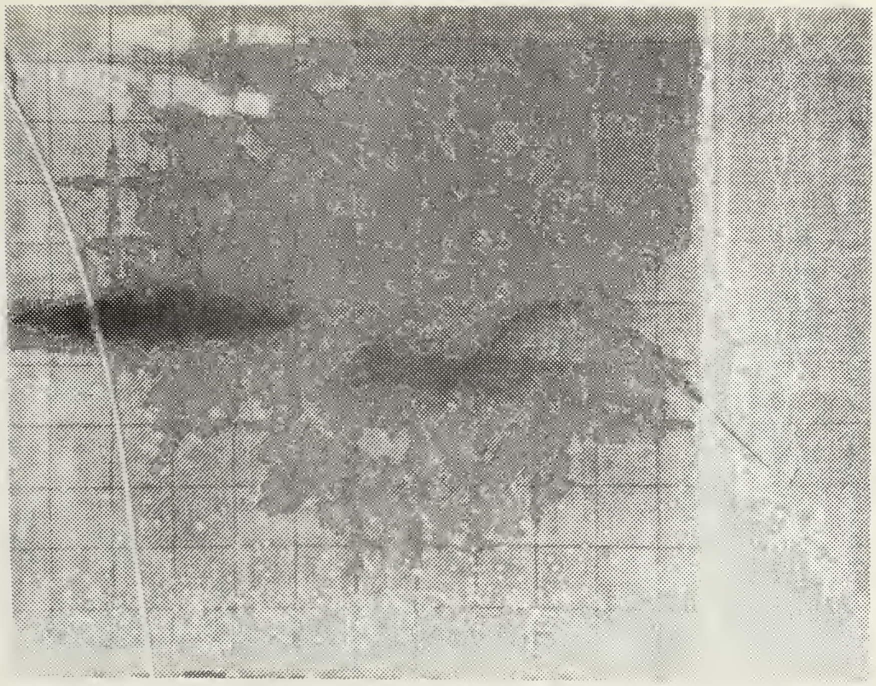
No. 92

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.5" H_2O

ΔT JET:
10°F



Injection:

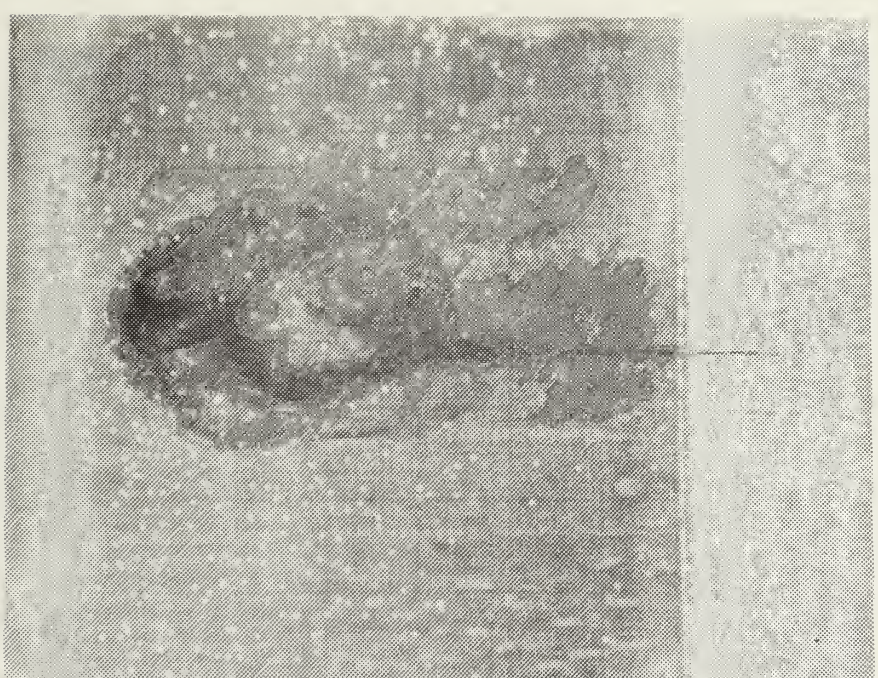
No. 93

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
1.0" H_2O

ΔT JET:
12°F



Injection:

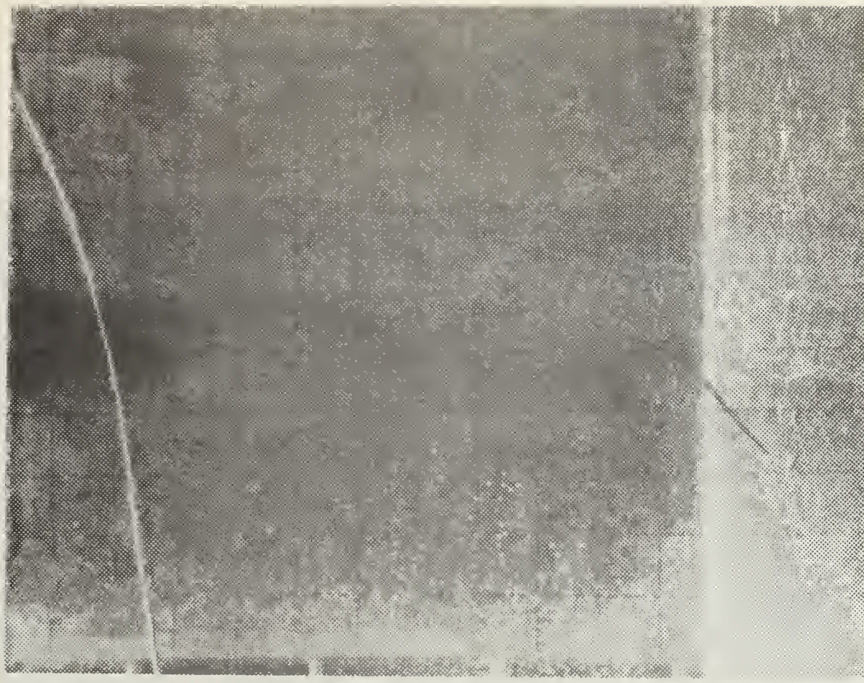
No. 93

VIEW:
TOP

ANGLE:
UP

TOTAL HEAD:
1.0" H_2O

ΔT JET:
12°F



Injection:

No. 94

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
10°F

Injection:

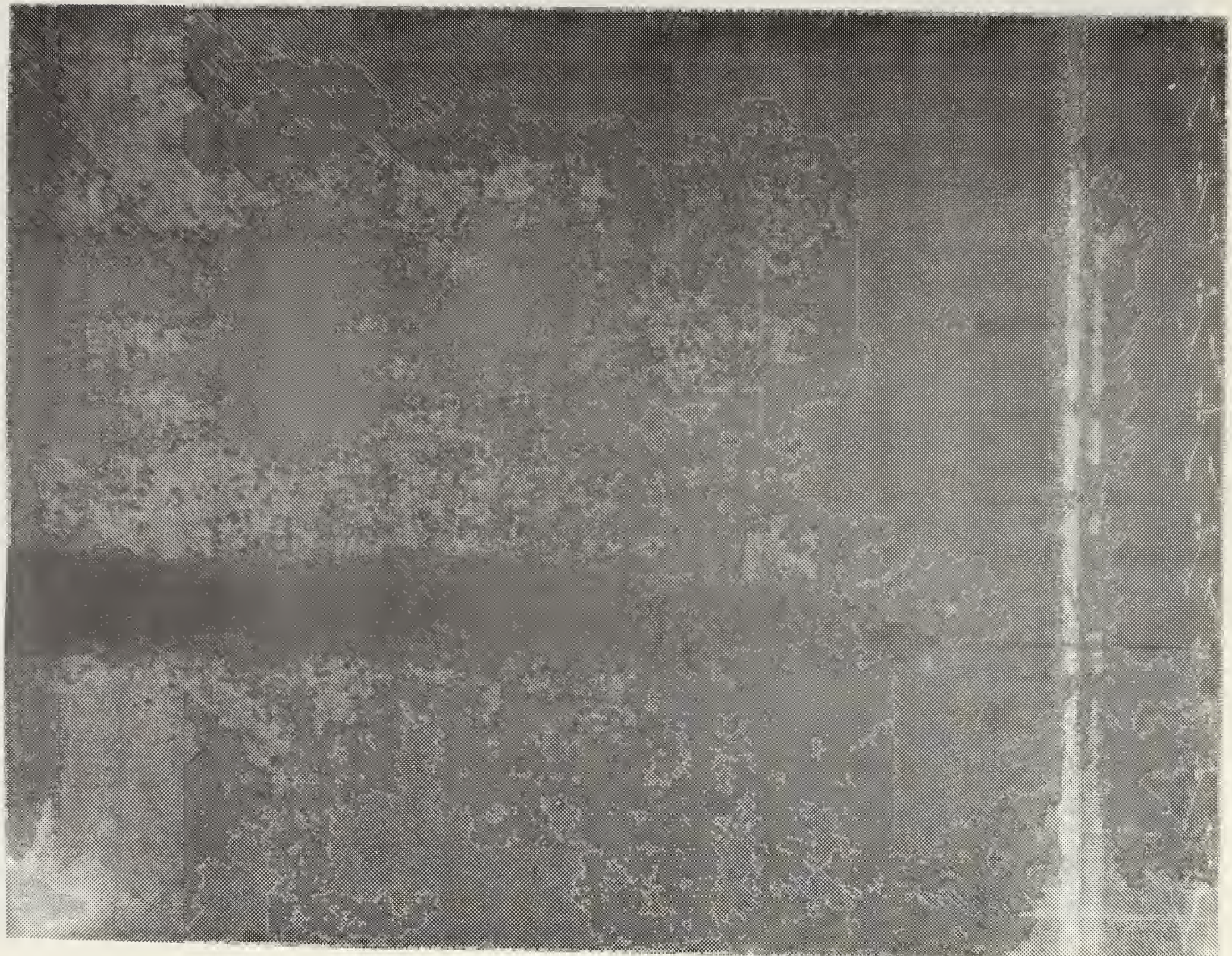
No. 94

VIEW:
TOP

ANGLE:
UP

TOTAL HEAD:
0.5" H_2O

ΔT JET:
10°F



Injection:

No. 100

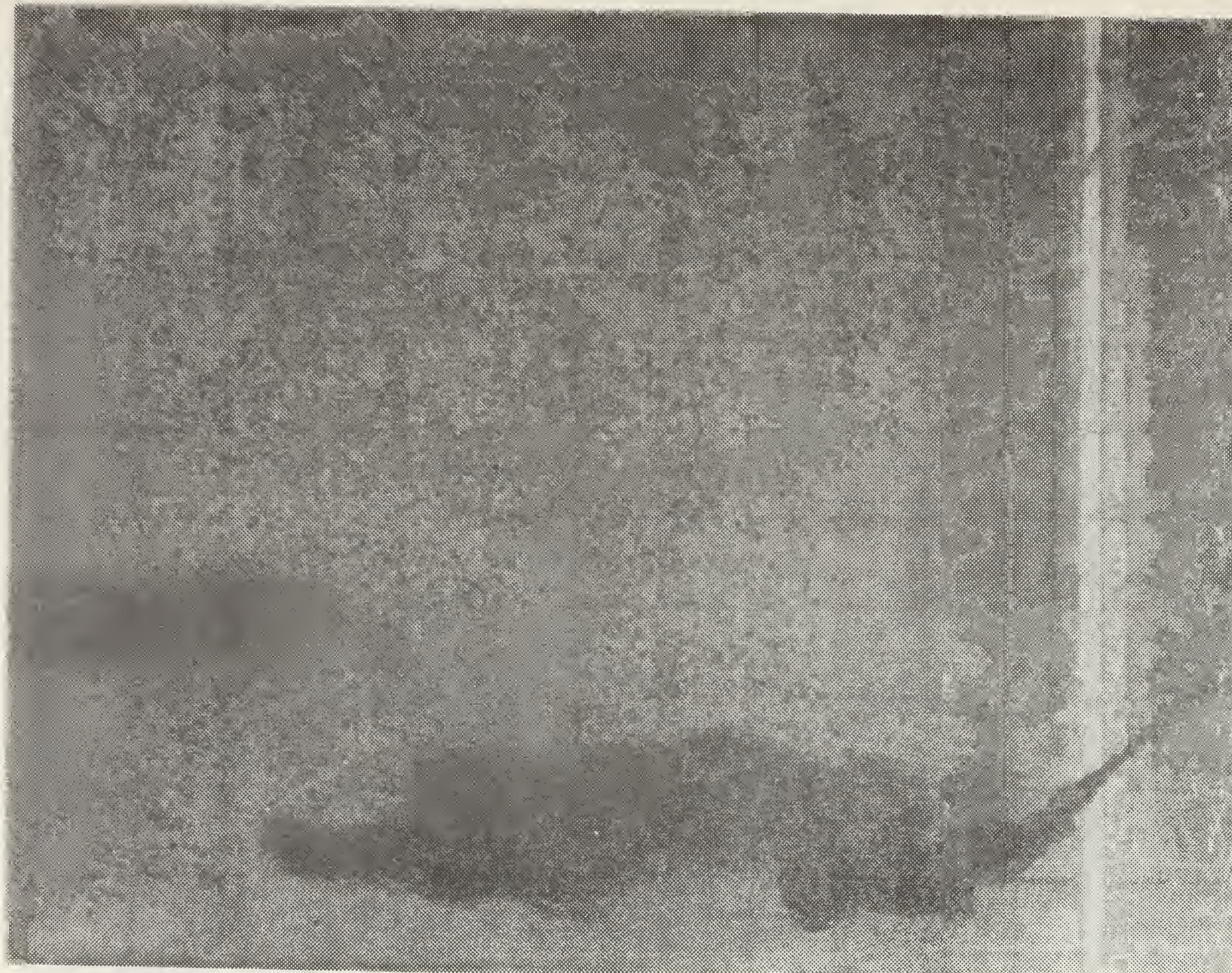
VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
2" H_2O

ΔT JET:
34°F

(Temperature gradient with injection lever at 83°F)



Injection:

No. 101

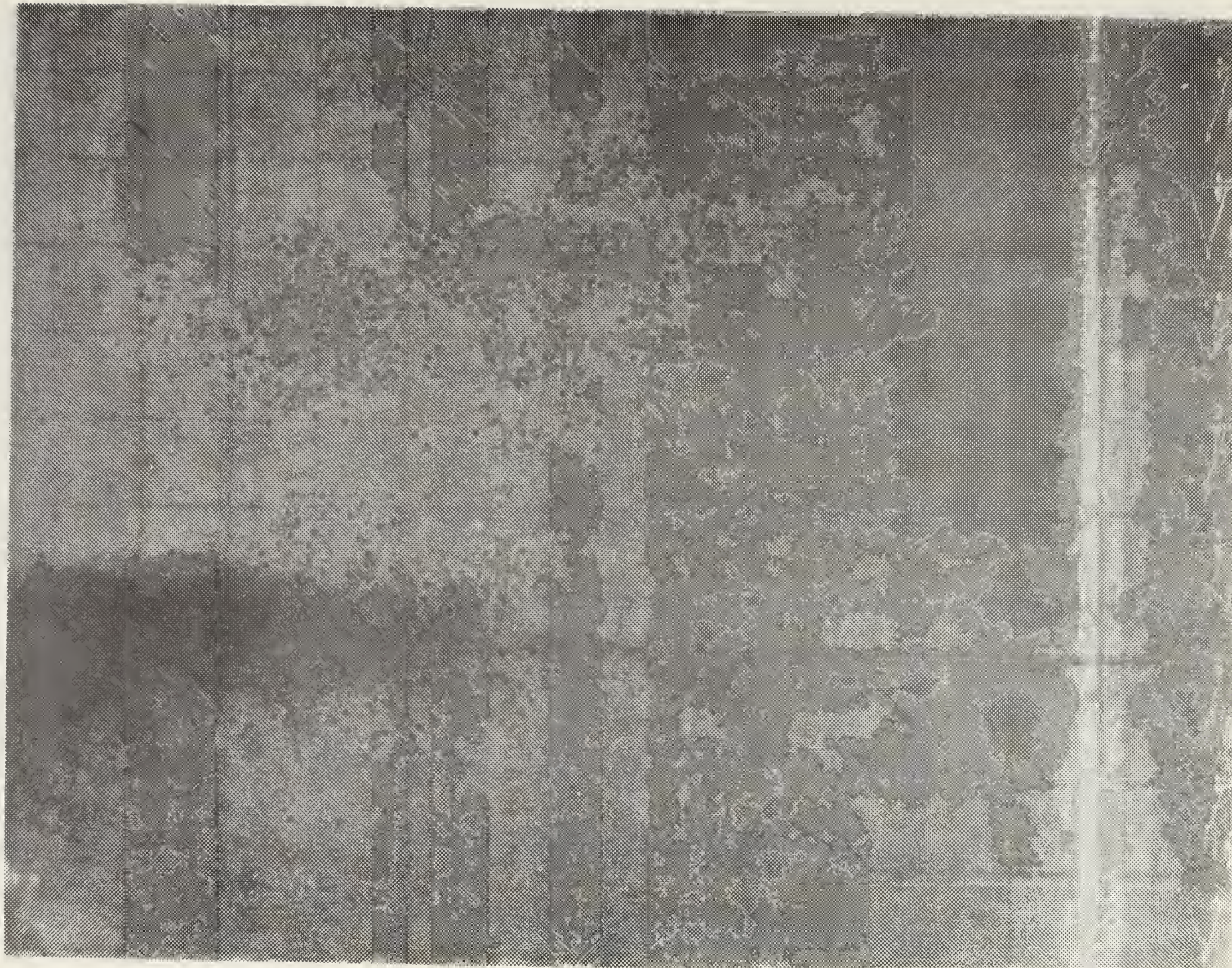
VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
2" H_2O

ΔT JET:
27°F

(Temperature gradient with injection level at 83°F)



Injection:

No. 102

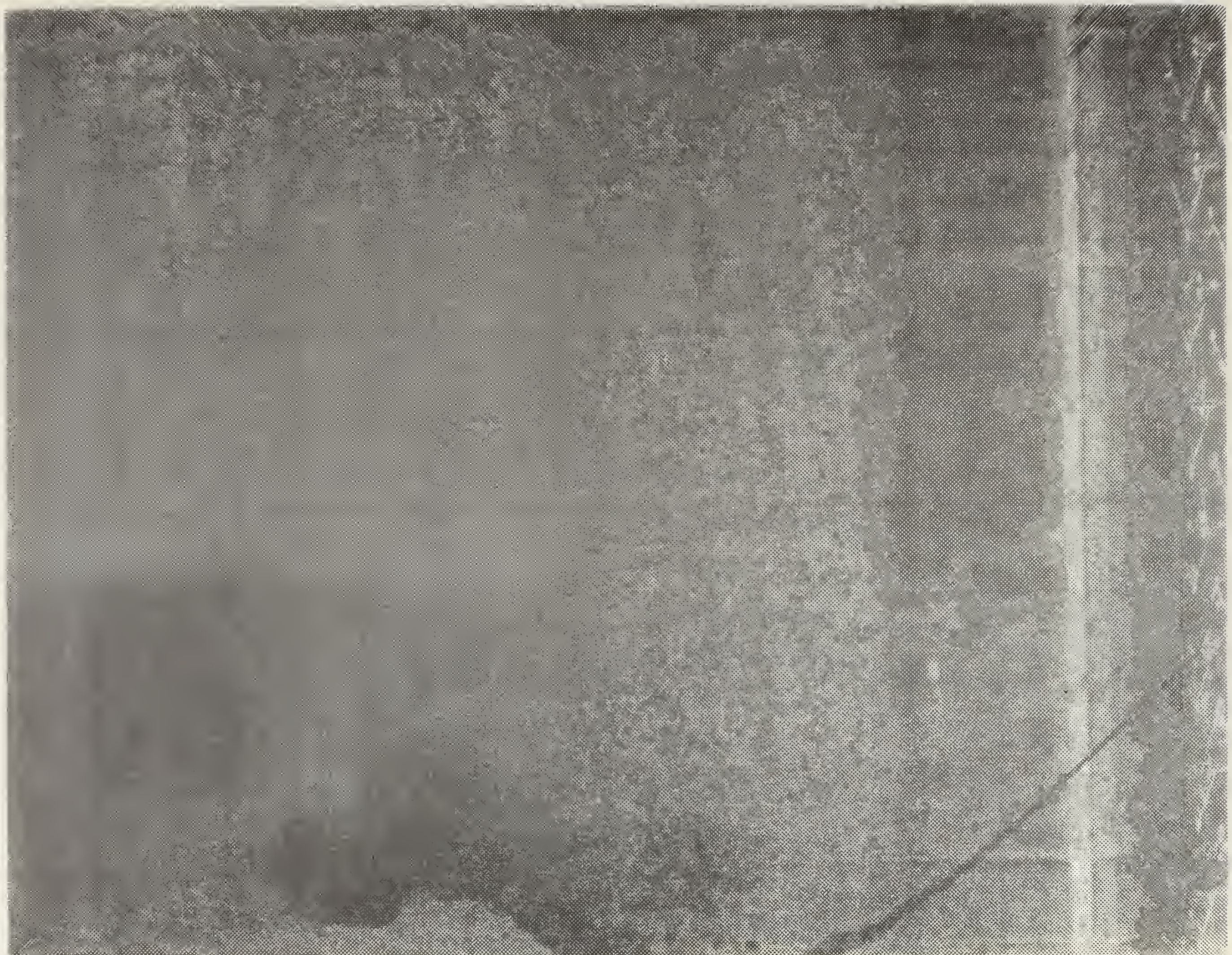
VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
2" H_2O

ΔT JET:
12°F

(Temperature gradient with injection level at 83°F)



Injection:

No. 103

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
2" H_2O

ΔT JET:
9°F

(Temperature gradient with injection level at 83°F)

Injection:

No. 104

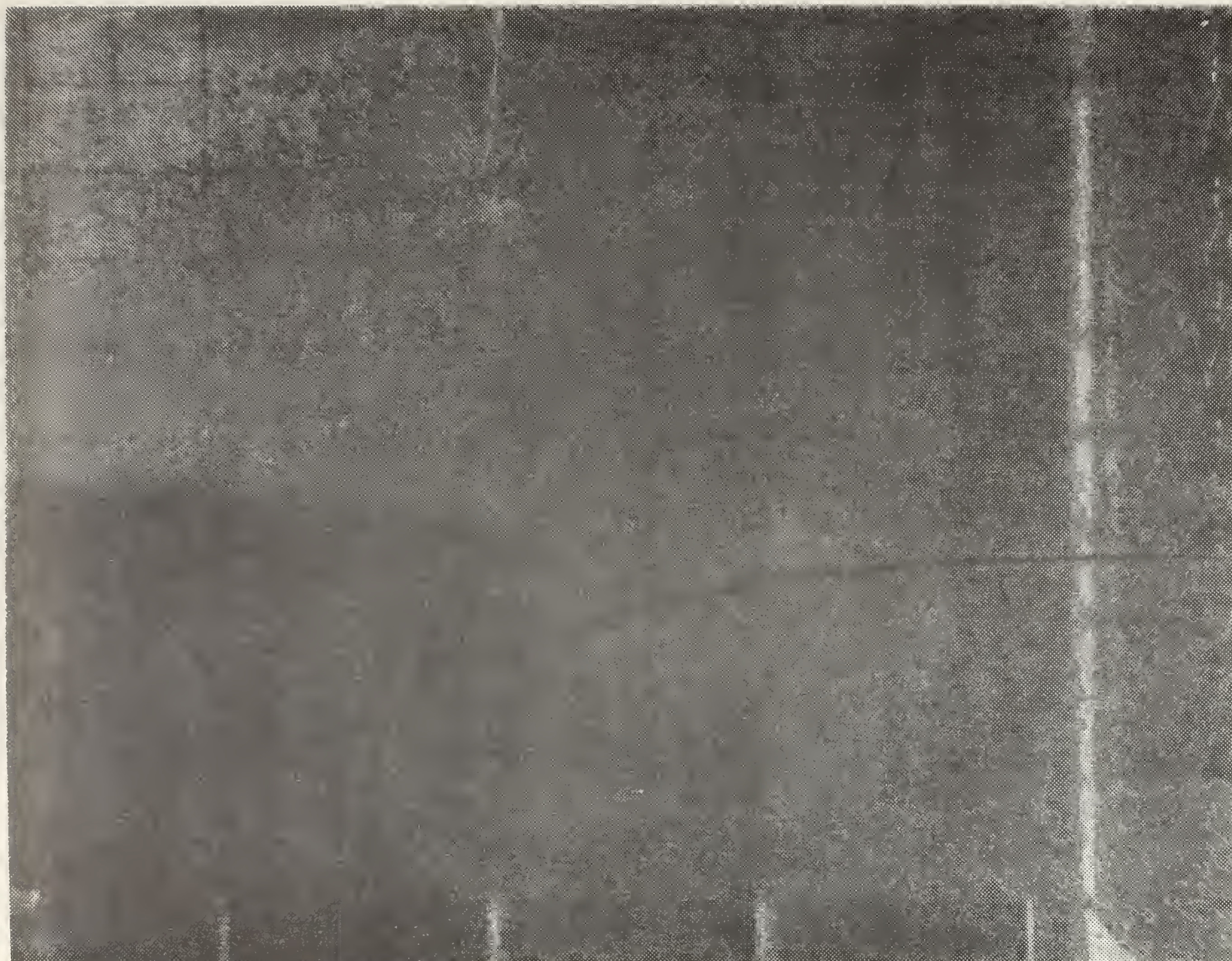
VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
2" H_2O

ΔT JET:
2°F

(Temperature gradient with injection level at 83°F)



Injection:

No. 105

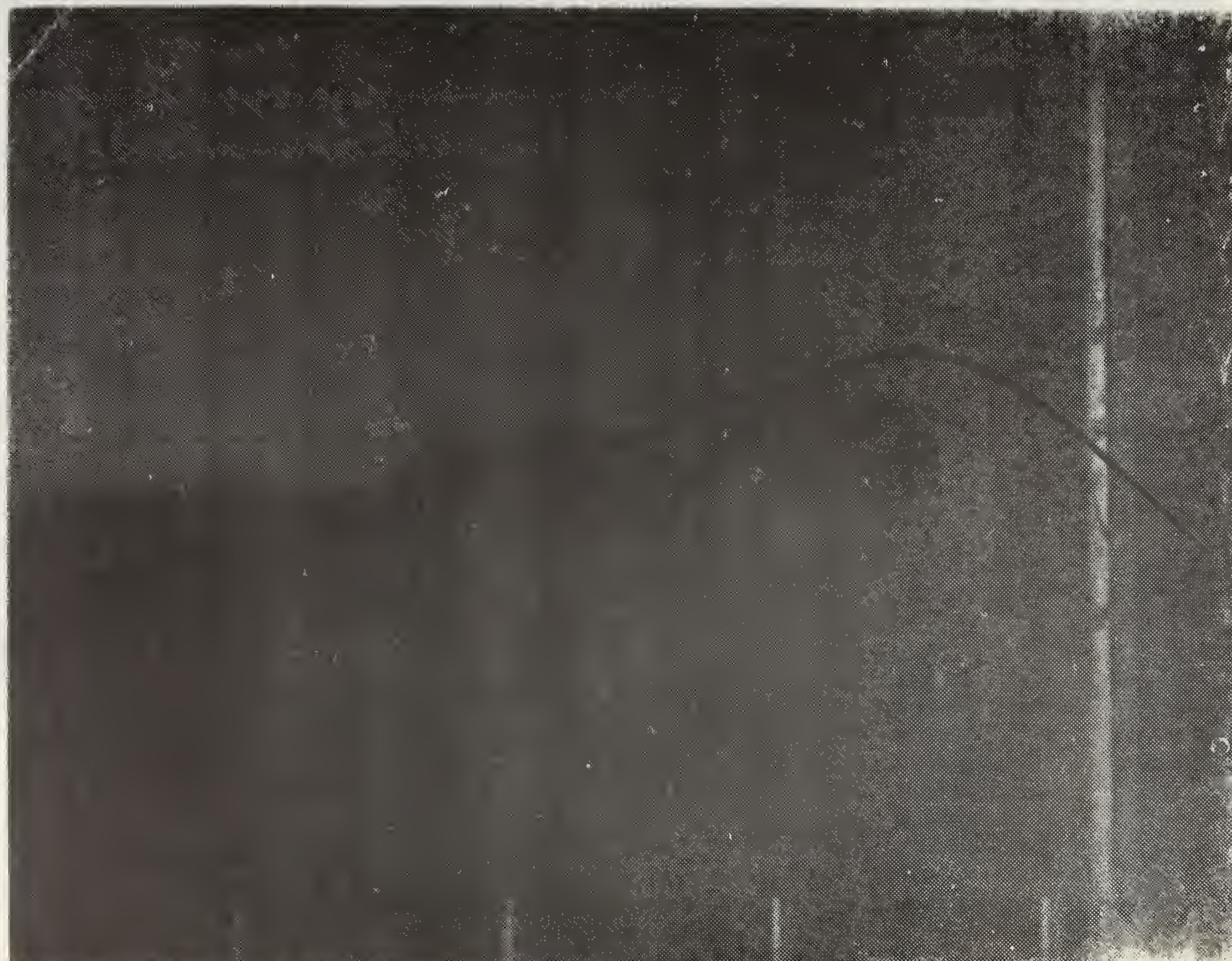
VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
2" H_2O

ΔT JET:
-12°F

(Temperature gradient with injection level at 83°F)



Injection:

No. 106

VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
2" H_2O

ΔT JET:
-12°F

(Temperature gradient with injection level at 83°F)

Injection:

No. 107

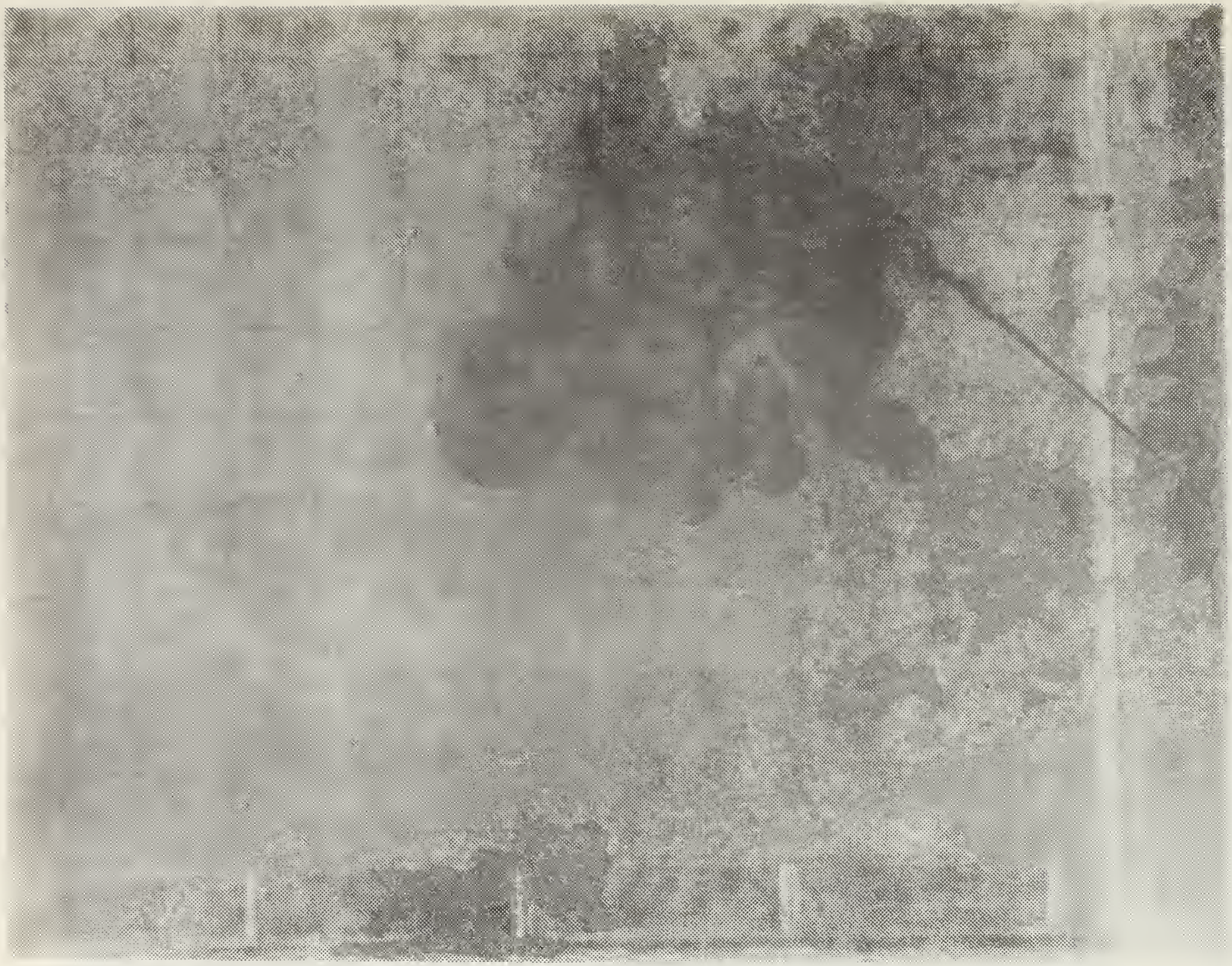
VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
2" H_2O

ΔT JET:
-18°F

(Uniform Bath
at 83°F)



Injection:

No. 108

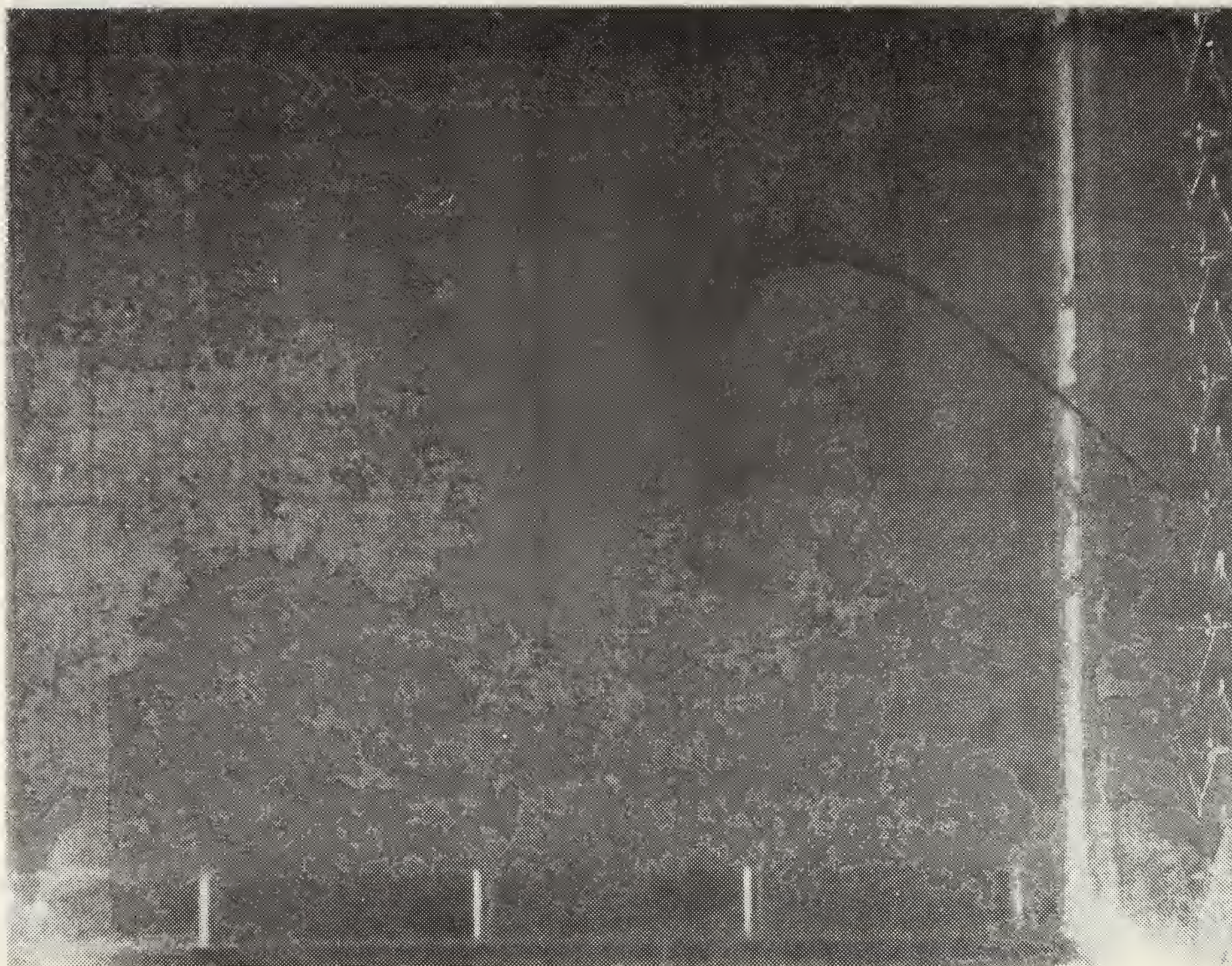
VIEW:
SIDE

ANGLE:
UP

TOTAL HEAD:
2" H_2O

ΔT JET:
-18°F

(Uniform Bath
at 83°F)



jection:

. 109

EW:
SIDE

IGLE:
UP

)TAL HEAD:
2" H_2O

T JET:
-19°F

Uniform Bath
at 83°F)

Injection:

No. 110

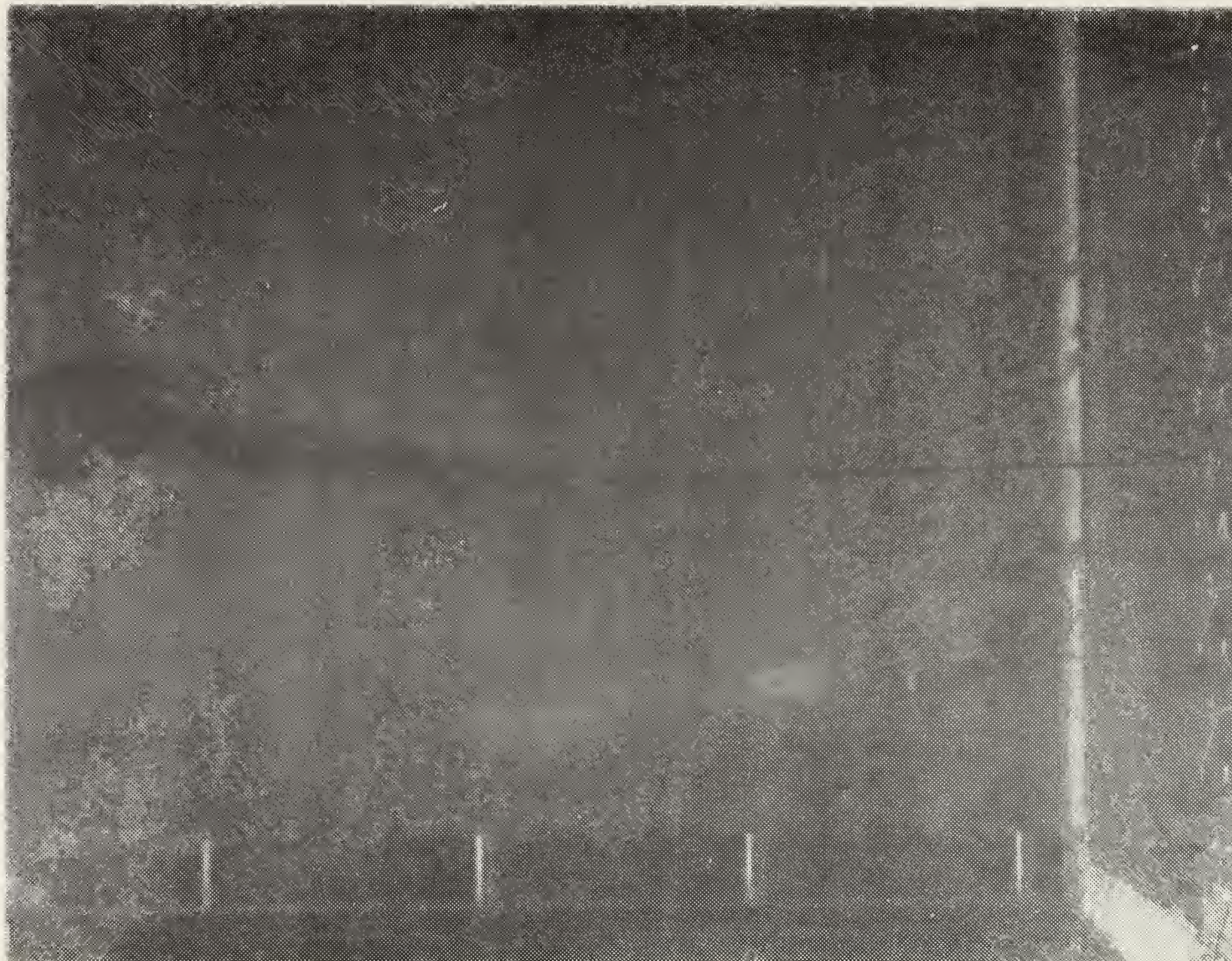
VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
2" H_2O

ΔT JET:
-19°F

(Uniform Bath at 83°F)



Injection:

No. 111

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
2" H_2O

ΔT JET:
2°F

(Uniform Bath
at 83°F)

Injection:

No. 112

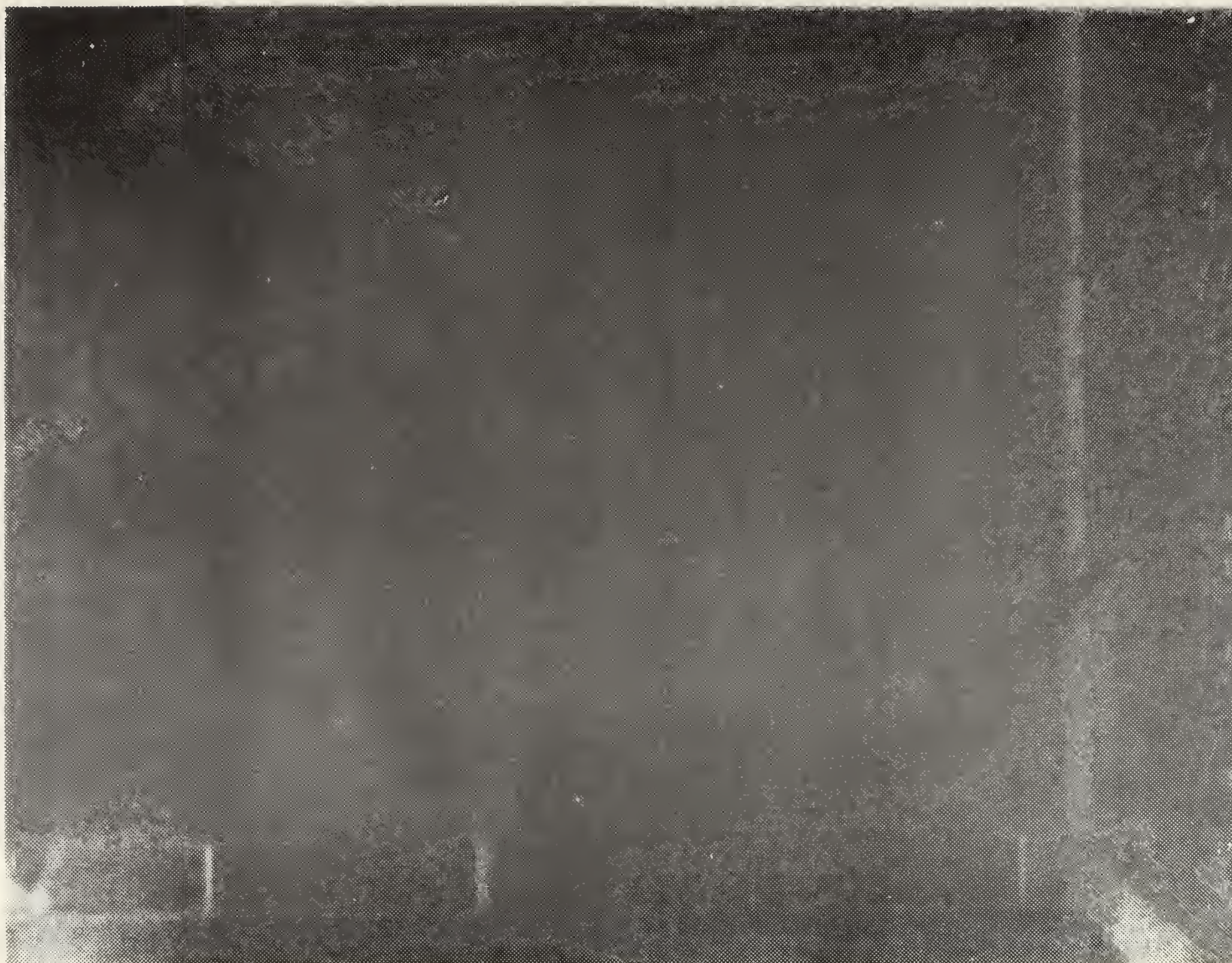
VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
2" H_2O

ΔT JET:
-10°F

(Uniform Bath
at 83°F)



Injection:

No. 113

VIEW:
SIDE

ANGLE:
DOWN

TOTAL HEAD:
2" H_2O

ΔT JET:
25°F

(Uniform Bath
at 83°F)

Injection:

No. 114

VIEW:
SIDE

ANGLE:
STRAIGHT

TOTAL HEAD:
2" H_2O

ΔT JET:
22°F

(Uniform Bath
at 83°F)

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ORIGINATING ACTIVITY (Corporate author) Naval Postgraduate School Monterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified
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REPORT TITLE

Jet Plume Development in a Thermally Stratified Medium

DESCRIPTIVE NOTES (Type of report and, inclusive dates)

Master's Thesis; June 1973

AUTHOR(S) (First name, middle initial, last name)

Robert Douglas Brown

REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June, 1973	114	7

a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
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3. ABSTRACT

The behavior of an incompressible jet injected into a stably stratified stagnant reservoir was studied in an attempt to define some new aspects of the thermal pollution problem. This experiment investigated the effects of injection angle, Reynolds Number (influence of turbulence), Rayleigh Number (influence of the total temperature of the jet), and reservoir temperature gradient on jet containment and flow stabilization. The nature of the study prohibited precise analytical evaluation of the results but observed tendencies could be qualitatively scrutinized to evaluate the inherent heat and transport problem. Results indicated the pronounced tendency of a reservoir temperature gradient to inhibit mass transport yet enhance heat transfer characteristics.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6811

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A-31408

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Thermal Pollution						
Thermal Stratification						
Jet Mixing						

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